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NOVEL POWER SOURCES  
for  
SURVIVAL SHELTERS  
(Contract No. OCD-OS-62-243)

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## NOVEL POWER SOURCES FOR SHELTERS

By Francis W. Lauck and Vern D. Overbye

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## I. SUMMARY

While the utilization of engine-generator sets for standby power is well-known, the possibility exists that some of the various "newer" chemical-to-electrical energy-conversion devices such as fuel cells, thermoelectric elements, etc., or the use of novel modifications of existing equipment, such as turbines and reciprocating engines, might be more suitable for shelter application. The purpose of this study is to examine systems utilizing various energy-conversion devices for the generation of power in order to determine advantages and disadvantages of these systems. A module of approximately 4KW is used as a convenient size for the illustrations. The results of the study suggest recommendations for future research on small power-generation equipment for use in shelters and disclose areas in which further development is needed.

Internal-combustion engines, coupled with generators or alternators, are currently the most promising methods for generating low power (up to 5 KW) in a shelter. The state of the art is such that with certain restrictions on storage and operating techniques, they could be "stored" for a ten-year period and then produce the desired quantity of power. The restrictions are that standard practices of replacing stored fuel at least once a year and periodically exercising the engine are recommended by all engine and engine-generator-set manufacturers that were interviewed. Lack of data on other possible storage methods and lack of general field experience indicates that carefully controlled tests should be conducted before recommending any changes in this procedure.

The utilization of engine-generator sets in the shelter create operating problems such as

1. the adverse heating effect upon the thermal environment,
2. heat rejection and cooling of the engine,
3. possible contamination of the shelter with toxic gases or vapors,
4. noise and vibration,

5. utilization of waste heat, and
6. operability in a closed or somewhat isolated environment.

These problems are considered under a Government project (A9)\*. They are of an engineering nature and the technology for their solution is known.

A summary of the findings in the study of other chemical-to-electrical energy-conversion devices and accessory equipment is as follows:

A. The Newer Energy-Conversion Devices

1. Thermionic Diodes

These are high-temperature, Carnot-cycle limited devices. Supplying heat via means other than solar energy or nuclear reaction would be extremely difficult due to the corrosive action of products of combustion at the high temperatures required of the heat source. The devices are essentially "go - no - go" devices in that unless the cathode is at a very high temperature, (approximately 2500° F.) the power output is nil.

2. Fuel Cells

These devices are not Carnot-cycle limited. Suitable efficiencies are readily obtained (more than satisfactory for shelter applications). Pilot-plant-type construction of prototype models indicate that the cost may well be competitive with engine-generator sets. Storage characteristics are undetermined. The main problem is reliability. Typical difficulties are membrane failure, failure of cell assembly, adhesives, poor contacts between membranes and electrodes, water contamination and gradual degradation of performance with time.

\* References are listed in Appendix 8 and referred to by a letter and number in the text.

5. utilization of waste heat, and
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The hydrogen oxygen fuel cell operating at 50-60% efficiency produces about one pound of water per kilowatt hour, but the water is contaminated and would require purification in order to make it potable.

The hydrocarbon fuel cells with reformers to generate hydrogen are between 25 to 35% efficient due to the inefficiency of the reformer.

Recent work on a propane fuel cell with a platinum anode and phosphoric acid electrolyte resulted in a better than 90% efficient cell. This is a recent development and insufficient data are currently available for evaluating the cell for the shelter application. However, this development appears promising and should keep under surveillance.

The heat dissipation problem is similar to that of engine generator sets, which is discussed in (A9) a concurrent project. However, the quantity of heat rejected from the fuel cell would be less by a factor of 2 to 5, depending on the cell efficiency.

The problem of toxicity of waste products does not exist for the hydrogen-oxygen fuel cell and, in general, due to higher efficiency, better utilization of fuel would be expected to be less severe for fuel cells than for internal combustion engines. However, fuel cells have the added problem of separating the products of chemical reaction from the reactants.

Fuel cells are discussed in Appendix 1.

### 3. Thermoelectric Elements

These devices are Carnot-cycle limited. They have good storage characteristics. A number of fuels (wood, coal, oil, gasoline, etc.) can be utilized as the chemical energy source; hence fuel storage need not be a problem. The cost of the units (which have rather low efficiency) is very high.

4. Magnetohydrodynamic Devices

The cost of the equipment is high and specialized accessories such as a cryogenic device are required to maintain the desired magnetic field with a reasonable power consumption. In general, these devices would be only suited for considerably larger power outputs (megawatt range) than anticipated for a shelter.

5. Solar Cells

Solar cells can be prefabricated in such a manner that the final installation is extremely simple. The energy source, radiation from the sun, is free, but the cost per kilowatt output for the cells is extremely high. The output of the cells is a function of the solar radiation at the time. If electrical energy has to be stored for use during dark periods (nights and rainy days), it would cost less to rely on stored energy from storage batteries for the entire emergency period.

6. Piezoelectric Effect

When the lattice structure of certain materials such as barium titanate is disturbed, large voltages are produced both during the disturbing process and when the strain is relieved from the material. The volume of electrons flowing in this rate-of-change-of-lattice-structure phenomena is extremely small. Therefore, these materials are satisfactory for producing a short duration spark, etc. However, the power produced per unit is so small that they could not be considered for generation of even 10 watts of power. In addition, these units require mechanical energy as a source of power. If this is available, it is highly probable that it will be either used as such or converted to electricity via a conventional generator.

B. Prime Movers for Novel Energy Conversion Devices

A hermetically-sealed turbine-generator unit appears quite feasible. This is the recommended device for further research because it inherently has good storage characteristics, can use easily stored fuels (wood, coals, etc.) and has the best possibility of being tested periodically after installation without subsequent packaging for 10-year storage.

1. Reaction Turbines (Closed Cycle)

Turbines utilizing pure reaction are not feasible for small (4KVA) turbine-generator units because of low mass-flow rates. Efficient operation at part load is difficult to obtain. A combination reaction-impulse turbine may offer some success. High-molecular-weight working fluids are required to limit wheel speed without resorting to expensive velocity or pressure compounding.

2. Impulse Turbines (Closed Cycle)

The impulse turbine (utilizing a heavy-molecular-weight fluid) is the most suitable prime mover for small turbine-generator sets. Design of an efficient 2 KVA unit would be difficult (because of friction and windage losses); design of an efficient 4 KVA unit appears to be possible; and the design of an efficient 10 KVA unit is very probable. Efficient part-load operation appears to be feasible. The size of the 10 KVA unit would probably be the same as the 4 KVA unit (partial admission would be used on the smaller unit by omitting some of the nozzles).

3. Radial-Inward Flow Turbines (Open or Closed Cycle)

The radial inward turbine has shown considerable success when used in some gas turbines (30 to 500 hp) and was also applied in a 450 hp waste-heat recovery system using Freon as a working fluid. The literature shows that this prime-mover is not suitable for low horsepower application (below 30 hp) because of the very low flow rates.

4. Gas Turbines (Open Cycle)

The possibilities of a reduced size conventional gas turbine were investigated, but difficulty was encountered with the mechanical effects of excessive wheel speed. Electrical problems do not appear too difficult to overcome. Generators and alternators are discussed in (A5).

5. Rotary-Vane Expanders

An experimental rotary-vane expander is described in the literature; the unit showed low efficiency, high wear, and

lubrication difficulties. Turbines operate at high speed and may require gear reduction, while the rotary-vane expander operates at a conveniently low speed.

6. Rankine Cycle Reciprocating Engines

Small reciprocating engines show no apparent advantage to be gained by using a heavy organic vapor for the working fluid. A higher temperature cycle using water as the working fluid should be used with these prime movers. However, the efficiency in the smaller sizes will be quite low.

Storageability may be better than a gasoline engine (no products of combustion are present) but worse than a hermetically-sealed turbine.

7. Monopropellant stems

If a suitable catalyst bed is maintained at 800 - 1200° F., a monopropellant fuel such as hydrazine ( $N_2H_4$ ) or hydrogen peroxide may be decomposed into high temperature and pressure gases and operate a suitable reciprocating or rotating prime mover. These systems have been developed for reliable, short burst, spacecraft control systems using radio-isotopic heat sources for catalyst heating. The specific fuel rate of existing power units (A10) range between 4 and 8 lbs. of fuel per horsepower hour in 10 horsepower sizes.

8. Stirling Engine

The unit has good thermal efficiency, but cost is very high and information on engine storage is nonexistent. It is anticipated that storage of the high pressure hydrogen (working fluid) would necessitate complicated engine-charging techniques prior to operation.

9. Unconventional Internal-Combustion Engines

Several engines with radically different construction features have been examined. None of these appear to offer much improvement in storageability or efficiency over conventional gasoline engines. Lack of high production facilities would make the unconventional engines more costly.

C. Fuels for Novel and Unconventional  
Energy-Conversion Devices

1. Nuclear Reactor

The fuels are stable and there is no radiation danger during stand-by storage or in the initial (zero power output) period. The short operating life in this case allows for the use of easily controlled reactions. The reactor and fuel cost is prohibitive. While specific designs for a shelter reactor are not available, information projected from the space program indicate a unit would cost about one-quarter to two million dollars per unit. (See Appendix 2 for details)

2. Radioactive Isotopes

These fuels would be decaying during the ten year stand-by period. Their scarcity would make widespread utilization extremely difficult.

3. Wood

Wood stores well and could be used with Carnot-cycle limited devices and other engines the same as coal and coke described below.

4. Coal and Coke

Storageability of coal and coke improves with age. These fuels have high heating values and the firing procedures are well-known. The fuel utilization is not necessarily confined to Carnot-Cycle limited devices. Coal and coke have been used extensively in gas producers in Europe and Japan to convert the solid fuel into gaseous fuels which may be used in internal-combustion engines.

5. Oil

There is some danger of gum formation during storage. The effects of this might be off-set in Carnot-Cycle limited devices via proper selection of equipment but would be difficult to design for internal-combustion engines. The storage of oil is discussed in (A9).

6. Gasoline

Conventional, catalytic-cracked gasoline stores at least six months at ordinary temperatures without sufficient gum formation to clog the carburetor of an internal-combustion engine. The straight-run gasolines store at least a year under the above conditions. Proper equipment selection for the Carnot-cycle limited devices and hydrogen formers for fuel cells might allow a ten year shelf life for gasoline (the gum would not prevent combustion). A study of the chemical structure of gasoline indicates that storing the fuel below 32° F. might reduce gum formation so that it could be used in gasoline engines after ten years storage. Gasoline should not be stored in copper-containing storage systems. The copper enters into chemical reactions with the gasoline to form gum deposits that could clog carburetion system (See Appendix 3)

7. Liquified Petroleum Gas

The storage of liquified petroleum gas and means for circumventing the safety hazards are discussed in reference (A9). In general, liquified petroleum gas seems to be a better gas for the shelter application due to its greater chemical stability over long periods of time.

8. Refuse

Low-moisture-content refuse (paper, cardboard, etc.) could be used as a fuel but it generally has a low heating value. The rapid combustion property of paper could cause temporary overheating and possible damage to the combustion chamber and boiler system.

Combustion Equipment

1. Solids

Combustion equipment for coal and the like is available. The existing equipment for wood and refuse combustion should probably be simplified for the shelter application to reduce costs.

2. Liquids

Combustion equipment for oils and kerosene is commercially available. Satisfactory burners for gasoline and alcohol are available, but the nature of the fuel probably warrants special testing of each manufacturer's equipment before approval for shelter usage.

3. Liquid Petroleum Gases

Combustion equipment is commercially available.

4. Producer-Gas Formers

This equipment has been manufactured for other applications. It probably should be redesigned for shelter use.

5. Hydrogen Formers for Fuel Cells

These devices are still in the laboratory stage.

6. Natural-Draft Chimneys

The low stack height for many shelter applications (7 to 10 ft.) causes chimney design to become critical. The literature search data should be supplemented by experimental data for a given application. Stack heights of 20 to 30 ft. greatly reduce design restrictions. The use of thermal-gradient density legs does not permit operation with high pressure losses in the system. Probably about 0.1 in. water gauge is the maximum allowable pressure drop in combustion equipment. However, this is satisfactory in many uses where it is not necessary to restrict the air flow, i.e., no filters or blast valves.

7. Forced-Draft Chimney

These remove the critical feature of stack height and are more foolproof than the natural-draft chimneys.

E. Boilers

Boilers are necessary in Rankine cycle power systems for transferring heat to the working fluid. Various types of

boilers are: 1) fire tube, 2) water tube, 3) flash, and 4) flash with secondary fluid. The boiler selection depends on the prime mover utilized in the system. The flash boiler (with a secondary fluid for preventing overheating of small quantities of organic fluids) appears most feasible from the cost and safety point of view.

F. Heat Rejection

1. Chimneys

Heat may be removed by the flow of air. Air flow may be induced by a chimney and a heat source. The characteristics of chimneys have been previously mentioned.

2. Condensing Vapor

Heat tubes using the evaporating-condensing heat transfer principle could be used to cause the upward flow of heat without pumps.

3. Circulating Liquids

Heat could be removed from the shelter proper via circulating fluids and a pump. Various schemes for circulating cooling liquids are discussed in a concurrent project (A9) for engine-generator sets. These schemes include both a fluid loop and the utilization of well water. They could be applied in a principle to any heat rejection system.

4. Heat Transfer by Evaporative Cooling

In addition to the conventional air-cooled condensers and evaporative coolers, an evaporative condenser using distilled water and wicking could be used because of the short period of operation. This latter method would eliminate the recirculation of liquid that has been exposed to radioactive contamination.

5. Earth Coils

Earth coils form a circulating liquid system to reject heat to the earth rather than to the atmosphere as do the systems



discussed in reference (A9). In this case, an appreciable quantity of the rejected heat is "stored" nearer the earth coil. The required coil length is a function of the local soil condition; therefore, the procedure for computing this heat transfer with "storage" is detailed in Appendix 3. If underground fluid flow occurs (such as in the case of underground rivers), the procedures of (A9) can be used with corrections for the heat transfer film coefficients that suit the situation. These are also discussed in Appendix 3, Section 2.

## II. RECOMMENDATIONS

- A. If electric power generating units are to be obtained immediately the gasoline engine-generator set with gasoline as the fuel is recommended as the chemical-to-electrical energy-conversion means. Periodic operation of the set with at least a yearly change of fuel supply would be the recommended procedure. Adapting engine-generator sets for shelter operation is being considered under a concurrent project (A9).
- B. If a power system and fuel supply is to be provided that will require the minimum of attention for reasonable cost, this investigation indicates that the following research projects should be considered (listed in order of our estimate of urgency of need except 5, which does not require research support and 6, which is peculiar to any system chosen):
  1. Investigate the cold storage of gasoline.
  2. Investigate the long-term storage of internal-combustion engines.
  3. Investigate turbines using a heavy organic working fluid.
  4. Investigate reciprocating steam engines using water as the working fluid.
  5. Observe progress in fuel cell development to determine when reliable fuel cells can be produced at a reasonable price.

6. Engineer accessory equipment to fit the electric power generating system and the shelter requirements.

### III. INTRODUCTION

The conventional engine-generator stand-by power generating units are not included in this report as they are being studied under a concurrent project (A9). However, means to improve their utilization in the shelter are discussed.

A second class of devices, which we call novel power sources, are considered in this project. The characteristic of this class is that the devices have already been developed and are receiving wide-spread usage in other applications. The problem is to revise the design of the particular device so that it is adaptable to shelter usage. The devices in this category are reaction turbines, impulse turbines, rotary vane expanders, reciprocating engines, Stirling engines, and unconventional gasoline engines that could be coupled with alternators or generators to produce electric power.

During the past decade, there have been improvements in the newer energy-conversion devices and heat sources such as thermionic diodes, fuel cells, thermoelectric elements, solar cells, nuclear reactors, and radioisotope consuming devices. These improvements indicate that these devices should be inspected as possible electrical energy producers for shelters. However, the high cost necessary to improve the state-of-the-art for these devices is clearly reflected in the high expenditures by both government and industry. Therefore, this survey evaluates existing newer conversion devices rather than results that may be obtained by expensive research programs.

Since the ultimate objective of this activity is to provide the shelter with a suitable power source rather than to develop a new type of power generator, it is necessary to inspect the auxiliary facilities (and the associated problems) that are required to allow the power generator to supply electricity to the shelter. The items inspected are fuels, combustion equipment for Carnot-cycle limited devices, chimneys or other means for rejecting gaseous products of chemical

reactions, boilers for transferring heat to the working fluid where applicable, and means for rejecting waste heat for Carnot-cycle limited devices to ambient heat sinks.

#### IV. DISCUSSION

##### A. Prime Movers for Conventional Stand-by Power Systems

###### 1. Gas Turbines

It will be shown in the next section that gas turbines are not suitable for power generation requirements below 10 KVA. In addition the storage problem would be similar to a reciprocating internal-combustion engine. The major supplier to small gas turbines is the Garrett Corporation.

###### 2. Reciprocating Engines

The reciprocating engines (gasoline and diesel) require special storage techniques and the conventional fuel is not sufficiently stable for ten year storage. These problems and the application of engine-generator sets for the shelter environment are considered under a concurrent project (A9).

##### B. Newer Conversion Devices

The literature published in the past few years on such subjects as thermoelectrics, thermionics, fuel cells, solar cells and magneto-hydrodynamics is practically overwhelming. This section of the report will present a brief description of how these newer conversion devices operate. Also, a short discussion of the current research and development effort as well as a list of commercially available devices is presented.

References used in preparing this section will be found in the Appendix at the end of this report. The appropriate reference is referred to in the text by a letter and numeral in parentheses for the Bibliography, Appendix 8. A "standardized" description for comparing various "newer" conversions is found in Appendix 7.

1. Fuel Cells

a. Description

A fuel cell (B2) is an electrochemical device which converts chemical energy directly into low-voltage, direct-current, electrical energy. It consists of two electrodes separated by an electrolyte. A fuel such as hydrogen is passed over the anode where electrons are generated. The electrons flow through the external circuit to the cathode where they are consumed by an oxidant, such as oxygen. Ionic conduction through the electrolyte completes the electrical circuit.

Fuel cells are classified in many ways (B3), namely, 1) the temperature at which they operate, 2) the type and form of electrolyte and 3) the type and form of the fuel. When classifying fuel cells by the temperature criterion, three groups are formed: 1) high-temperature cells typified by molten-salt electrolytes (1100-1200°F), 2) medium-temperature cells like the Bacon hydrogen-oxygen cell (400°F) and 3) the low-temperature cell typified by many of the hydrogen-oxygen cells that operate up to the boiling point of the aqueous electrolyte. In classifying fuel cells by type of electrolyte either basic or acidic systems are designated. Classification by form of electrolyte would include membranes. When fuel cells are classified by form of fuel, this designates whether the fuel is gaseous, liquid or solid. Another method of classification is the individual fuel itself.

b. Research efforts

The area in which much research on fuel cells is being done is in the space effort (B3). Both the Apollo and Gemini programs are relying upon fuel cell research to solve the problems of power for space craft since a fuel cell power supply has been selected. The reasons which make hydrogen-oxygen fuel cells desirable for space applications are primarily the following: 1) the bulk of fuel cell units is compatible with space

limitations in spacecraft, 2) the specific power output (KW/lb) is also favorable for space applications and 3) the product of reaction, water, is useful. The annual expenditure for fuel cell research including the Apollo and Gemini programs is approximately \$25 million. Appendix 1 has a detailed discussion of fuel cells.

c. Actual Devices

Pratt and Whitney Company has developed a 500 watt fuel cell (B6) which was commercially sold. The price, availability, and reliability of this device is not available. Many other companies including General Electric, Allis-Chalmers, Union Carbide, Chrysler Corporation, Tapco, Ionics, Kellogg, Lockheed Missile and Space Company, . . . o Research Lab., Surface Processes R. & D. Corporation, Mine Safety Appliances, Argonne National Lab., Allison Division of General Motors, Electro-Optical Systems, Inc., Aerospace Corporation, and Electric Storage Battery Company have done or are doing research on various types of fuel cells and have produced many laboratory models, but have not yet commercialized any units.

2. Thermoelectric Effects

a. Description

A thermoelectric device (A4) is one in which heat is converted directly into low-voltage direct current. The principle upon which these devices operate is the well-known effect that produces an emf in a thermocouple. An ideal material would have an infinite electrical conductivity, zero thermal conductivity, and produce a high emf. Much research on material development has been done in the past and more remains to be done. The theoretical efficiency of the best existing materials is about 20 per cent; further improvement in the past year has been negligible. The actual over-all thermal efficiency of a complete system is reduced to less than 4 per cent by Peltier losses at the interfaces, electrical contact losses, heat losses through the

insulation, and combustion losses. The mode of operation of all thermoelectric devices is similar; the differences in output arise from the materials used and permissible operating temperature. The most common material used at present is lead-telluride, which is restricted to operation at temperatures below 1100°F.

**b. Research Efforts**

- (a) Continuing research effort to develop cheaper and more efficient thermoelectric elements is in progress. Although a great reduction in the specific cost (CS) has been achieved (from \$1000/watt to less than \$50/watt), the elements are still too costly to compete in other than very special applications. Several contracts to develop 50 to 150 watt generators for the military are in progress (C9 and C10). Potential applications suggested in the literature are: 1) cathodic protection, 2) portable power sources, and 3) thermoelectric-powered blowers in warm air furnaces (C6). Cost is still a major obstacle in these efforts.

**c. Actual Devices**

The prime suppliers of off-the-shelf thermoelectric units are Minnesota Mining and Manufacturing Company, Texas Instruments, and Westinghouse (Lima Aerospace Division). The commercially available units are listed below. In addition, the C. A. Olsen Company has produced several thermoelectric-driven fans for hot air furnaces on a special order basis.

<u>Supplier</u>	<u>Rating (Watts)</u>	<u>Price</u>	<u>Efficiency</u>
3 M Co.	2	-	1.141%
	4	250	1.36
	8	325	1.70
	15	425	1.70
Texas Inst.	8	800	-
Westinghouse	3	150	-
	100 *	10,000	2.50
C. A. Olsen	130 *	7,500	-

\* Special order, single units, approximate prices

### 3. Thermionic Emission

#### a. Description

The field of thermionic emission is of interest as a source of power (especially in the space program) for several reasons, among these are its high current density (10 watts/cm<sup>2</sup>), high-temperature heat rejection which would require a small space radiator, and simplicity of operation. The operation of the thermionic diode (A4) depends upon the fact that when a cathode is heated to incandescence, electrons are given off by thermionic emission. These electrons are collected on a colder anode from which they flow to the external circuit. However, a repulsive field is created by the electrons between the cathode and anode. This "space charge" greatly reduces the power output of the device.

Some investigators introduce a plasma-producing gas into the region between the anode and the cathode which ionizes when it comes in contact with the hot cathode. This phenomenon is used to reduce the space charge effect. Another method of neutralizing the space charge is to use a vacuum diode in which the space between the cathode and anode is made very small. Although this spacing is a function of the power density, work function and temperature, for high performance, this spacing should be less than 0.001 inch. Consequently, this method is seldom used because of manufacturing difficulties.

The plasma cell maintains the appropriate positive ion density (usually cesium) in the interelectrode region to neutralize the space charge. This type of diode allows much greater electrode spacing and is primarily the only device of interest at present. A plasma thermionic diode does not operate at all below a temperature of approximately 2400°F. This condition causes great material problems. The cathode in the usual plasma diode is made from a refractory metal which is easily oxidized by ordinary combustion heat input. Therefore, a protective coating of some kind is necessary to prevent this oxidation and in so doing lengthen the life of the diode (D3).

b. Research Effort

Much work is being done on protective coatings, but to date no long-lived devices exist.

Some successes have been achieved using thermionic devices in nuclear reactors where the oxidation problem is not serious, and in heating with solar energy (F1) where the refractory metal cathodes can be kept in a protective vacuum environment. The problem with solar energy conversion is associated with concentrating the solar energy so that the high operating temperatures can be maintained; work on solar collectors is in progress.

Much research effort has been slanted toward space application here solar or nuclear energy is a convenient source of heat.

c. Actual Devices

The only company which produces thermionic devices commercially is Thermo Electron Engineering Corp., Waltham, Mass: Model A103, 30 watts, \$3,800.00, solar heated.

4. Magnetohydrodynamics (MHD)

a. Description

Because of potentially high over-all efficiencies, MHD systems are of particular interest for the large-scale generation of electricity (megawatt sizes). The principle of operation is similar to that of a conventional electrical generator (E2) except that a gaseous ionized medium is used instead of metallic conductors. The movement of this gas through a magnetic field produces a component of electrical current transversely to the path of the gas stream and to the magnetic field. Electrons in the hot stream of ionized gases are deflected by the magnetic field, enter one electrode, complete the circuit through the external load, and re-enter the gas stream through the opposite electrode.



Very high temperatures are required (up to 5,000°F) since ionized gases (good conductors) are produced only at high temperature. Furthermore, a seeding material such as an alkali-metal salt is added to the gas stream to increase the conductivity. The output is direct current, although some schemes have been proposed to produce alternating current.

b. Research Efforts

MHD systems are in a very early stage of research development and probably will not become practical for many years. Problems involving materials of construction able to withstand and contain the very hot gases present one of the greatest difficulties, along with the problems of maintaining large magnetic fields without expenditure of large amounts of power and also the task of producing ionization in the gaseous working fluid. Superconducting magnets (ES) offer some hope for resolving the magnetic field problem, but keeping the electromagnet at cryogenic temperature near hot ionized gases is a difficult problem. Research is being conducted in all of these areas.

c. Actual Devices

Our study revealed no actual commercially existing MHD devices, and the low-power experimental devices do not appear to have net power output, since conventional electromagnets require large amounts of power.

5. Solar Cells

a. Description

Solar cells are the most advanced of direct energy conversion devices (F1). The most common form consists of a very perfect silicon crystal which is treated with traces of impurities that introduce extra positive and negative charges on the two sides of a thin wafer. These extra charges remain on their respective sides of the junction until light energy strikes the crystal. Radiant energy further disturbs the electrical balance of charges and starts them moving toward the surfaces and the junction.

The current flow continues as long as light strikes the crystal. The physics of this process is fairly well understood. The theory indicates that 25 percent of the incident radiation can be converted to electricity. Under special conditions perhaps 50 percent could be converted to electricity. The best laboratory results to date have shown that about 14 percent of the incident radiation is converted to electricity. For ground use, the problems of size and cost become very important. As an example, a 10 KW generator suitable for home use would cost close to two million dollars and occupy 100 square yards (A4).

b. Research Effort

Current research appears to be concerned with producing cheaper cells and more effectively using the cells by concentrating the solar radiation (F4). The space effort is supporting much research.

c. Actual Devices

Solar cells are manufactured by many companies; foremost among these companies are General Electric, Hoffman Electronics, and International Rectifier. The cost of solar cells is high. A 10 KW unit would cost approximately \$1,500,000 based on the cost of \$6.00 for a 40 milliwatt commercially available cell (Allied Radio) for quantities from 100 to 999.

6. Laboratory Curiosities

The study revealed (G3) several laboratory curiosities for direct energy conversion. None appear promising.

a. Workman - Reynolds Effect

This device utilizes the principle that freezing a solution of water and inorganic chemical (ammonia salts for instance) causes a potential to be generated across the ice-liquid interface. Voltage is dependent upon solute concentration and current depends upon freezing rate. Experiments have shown potentials of 230 V. and currents of 1 A.

b. Thermomagnetic

Alternately heating and cooling a permanent magnet in the neighborhood of its Curie temperature causes a change of flux and generates a low frequency current in the coil. Amount of power depends on rate of flux change, hence rate of heat absorption and rejection.

c. Austin Effect Generator

Heat is applied to a sandwich consisting of a steel plate, a vitreous enamel coating and a silver electrode. A current is generated which lasts for as long as a half hour after heat is removed. The physical mechanism that produces the current is not yet well understood.

d. Electrokin. Effect

When a fluid flows past a solid surface, a current is generated. This effect is called "streaming potential." It is most pronounced when the fluid in the pipe is forced through a porous solid and the potential measured between an electrode upstream of the obstruction and another electrode downstream.

e. Pyro-Electric Effect

When an oriented crystal such as tourmaline or tartaric acid is heated, a potential is generated between its two faces as it cools.

f. Piezoelectric

Certain materials such as barium titanate, strontium titanate mixtures, etc., have the property that while they are in the process of being deformed or being relieved of a stress, high voltages are produced across certain dimensions of the crystal. The associated current is extremely small, and the power output is almost nil as far as a shelter power supply application is concerned. These crystals or crystal mixtures are commercially produced for such applications as sonar systems, dental drills, pressure gauges and phonograph pick-ups.

These materials are dielectrics and have high internal resistances; suitable areas for their application would be more in the order of charging a condenser than producing appreciable electric power.

g. Organic Fuel Cell

It works like an inorganic fuel cell except that it "burns" organic waste material.

h. Biological Fuel Cell

The biological fuel cell functions essentially in the same manner as the hydrogen oxygen fuel cell. In addition to the hydrogen section, a bacterial reaction has to occur to produce the hydrogen. These are low power devices and thought of as a "waste" disposal means rather than power producers. The main problem in their development is the fixation of the bacteria at the electrode so that the hydrogen is formed where it can be used for producing electricity. Appendix 1, Section 2, has additional information on this subject.

i. Nernst Effect

The Nernst effect is the creation of an electrical potential perpendicular to both an applied temperature difference and an applied magnetic field.

C. Novel Conversion Devices

1. Rankine Cycle

a. General Principles and Reason for Selection

A low-power Rankine cycle, using a working fluid other than steam, is discussed here. The reason for discussion of such a cycle is that by proper design and choice of working fluid, a "small" power unit could be developed which would not require periodic operation or attention.

The Rankine cycle may be considered basic to all vapor cycles showing reasonable thermal efficiency. The

cycle, which is well defined in all thermodynamic textbooks, consists of an isentropic compression of the liquid working fluid to boiler pressure, constant pressure heating (evaporation) in the boiler, isentropic expansion of the vapor through one of a variety of expansion devices, and constant pressure cooling (condensation) in a condenser. The cycle was formerly used extensively in both stationary and portable equipment, but is now essentially displaced in all but the largest central-power stations and ship-propulsion systems in favor of the more adaptable internal-combustion engines and electric motors.

The reason that a well-known extensively-used power cycle is considered novel in this study is primarily due to the fact that it may be applied in new applications due to recently successful theoretical and experimental investigations and advances in materials development. This section will consider application of the Rankine cycle with various low-horsepower prime movers and suitable working fluids.

The incentive to develop low-horsepower units using the Rankine cycle has been stimulated throughout the 20th century by the desire to harness solar energy for terrestrial applications (and more recent space applications). It was early recognized that the possibility of replacement of large coal-burning central-power stations by solar-energy plants was quite remote because of the large initial expense of solar collectors (literally square miles of collectors are involved to obtain megawatt power). However, the great need for small power plants to serve remote areas is present today as well as in past years. Hence, low-temperature Rankine cycles have been proposed, but success has been rather meagre. The more recent success, which will be detailed below, has now indicated that the prime concern may well be the collector rather than the prime mover.

The military was induced to investigate small-horsepower external-combustion cycles (Rankine, Stirling, etc.) in an effort to develop silent power units for communications between front-line reconnaissance missions as well as silent power units for propulsion of small boats.

The space program also has stimulated a desire to utilize solar or nuclear energy with small Rankine cycle units because of the difficulties and cost involved in transporting fossil fuels to space stations and satellites to fuel internal-combustion engines. It is more appealing to provide a heat source (nuclear or solar for use with an external-combustion engine.

The benefit to be derived from an external-combustion engine in the Civil Defense program is quite obvious when it is considered that the storage lifetime of internal-combustion engine fuels (gasoline, diesel fuel, LFG, etc.) and the engines themselves is quite short when considered in terms of the Civil Defense program. The fuels for external-combustion engines may include the above fuels as well as coal, wood, and coke (good storage characteristics). Also, solid fuels may be more readily available in unusual circumstances than the more highly refined liquid fuels.

b. Fuels

The advantage of an external-combustion power cycle is that many different fuels may be used. Also, each fuel may be burned under ideal conditions without regard for the variation of prime-mover speed. As an example, it may be desirable to reduce the flue gas temperature prior to using it in a flash boiler. The flue gas temperature may be reduced by control of either primary, secondary, or diluent air such that combustion is completed and the flue gas is at the desired temperature. The fuel-air ratio in an internal combustion engine is quite restricted to insure combustion (except when the "stratified charge" technique is used) and the fuel-air ratio usually must be changed with speed and load.

In the "stratified charge" technique, an adequately rich fuel mixture is injected near the spark plug to insure ignition, and the resulting heat allows ignition of the remaining, substantially leaner, mixture. This allows combustion with over-all fuel-air ratios of 1/16 to 1/50 rather than the conventional 1/15.

The advantages and disadvantages of various fuels and combustion methods suitable for a Rankine cycle are given later in this report.

C. Boilers

One of the most complicated, expensive, and dangerous components of a Rankine cycle system is the boiler. The chief reason that induced 19th century inventors to develop air engines and internal-combustion engines was the wide-spread fears of boiler explosions. However, modern design methods and materials have reduced the explosion hazard to a minimum. The various types of boilers will be described.

c-1 Fire-Tube Boiler

As the name implies, this shell-and-tube boiler consists of water in the shell with the hot flue gases passing back and forth through tubes one or more times prior to being discharged. Heat loss is reduced due to the fact that the combustion chamber is surrounded with water. Many modern package boilers are the fire-tube type.

Since the boilers in this study are concerned with small prime movers located nearby, the fire-tube boilers formerly used on steam automobiles are of major interest (H1). One of the earliest popular commercial steam automobiles, the Stanley, used a single-pass, fire-tube boiler. It was realized that during an explosion, the sudden depressurization would result in release of large amounts of water vapor. To prevent such an explosion, the shell was reinforced by wrapping piano wire in the asbestos insulation. Also, a fusible plug was placed in the feed-water line so that lack of water flow would cause the plug to melt and prevent an explosion due to a low water level in the boiler.

In general, the fire-tube boilers require a short initial period of time to produce the required steam pressure; they also contain a large amount of energy that may be suddenly released in an explosion and they require costly fabrication procedures.

When operation with superheat is required, a superheater must follow the fire-tube boiler.

c-2 Water-Tube Boiler

Again, as the name implies, the water-tube boiler consists of a number of tubes filled with water connecting a water header on the bottom with a steam header on the top. The combustion gases pass over the water tubes and out the stack. Many large central-power-station boilers are the water-tube type.

The water-tube boiler was also used in the steam automobiles produced shortly after the first world war. The Doble water-tube boiler was used on many gas-propelled buses, cars and boats in Europe prior to World War II. The presence of water in small tubes rather than in a large shell was often advertised as a feature that made an "explosion-proof" boiler.

When operation with superheat is required, a superheater usually follows a water-tube boiler.

c-3 Flash Boiler

The flash boiler is an extremely simple device when compared with either the fire-tube or water-tube types. It is made essentially of one continuous length of small-diameter tubing. The working fluid enters one end of the boiler and leaves the other end either as saturated or superheated vapor. The counterflow principle is often used (the feed liquid enters the bottom and vapor leaves the top, while the hot combustion gases enter at the top and leave at the bottom). Hence, the use of a superheater after the boiler is not necessary.

The early steam-automobile makers preferred the "stored power" nature of a fire-tube or water-tube boiler, i.e., the boiler could continue to vaporize large amounts of fluid during low-power operation to build up a reserve steam supply for later high-



power operation. However, the trend among present day steam-car enthusiasts is to use a flash boiler (which is claimed by one to be completely explosion proof) of sufficient size to handle the most severe power demands and control the heat input more precisely with modern controls.

The flash boiler was used in all the low-power Rankine cycle systems found in the study when a small boiler was included in the experiments. The boiler used in the SNAP 2 system (H3) (Rankine cycle using mercury as the working fluid) used the flash principle in which a concentric tube (counter-flow heat exchanger) heats the mercury with liquid sodium from a nuclear reactor. Hence, the flash boiler appears to be the most modern, reliable, low-cost sign for low-power Rankine cycle power systems.

c-4 Flash with Secondary Fluid

One investigation in which Freon 114 was being heated in a flash boiler involved decomposition of the working fluid that may have been due to the hot spots that formed on the superheater portion of the tube during startup. This problem probably may be avoided by using a flash boiler with a secondary (higher boiling-point) fluid in an annulus (formed by a concentric tube) around the boiler tube such that the hot combustion gases cannot make direct contact with the working fluid. An alternate method is to immerse the entire tube in a secondary fluid. In either case, the secondary fluid may be refluxed to prevent loss and yet avoid high pressure. The refluxing equipment would be a simple gas cooling column to condense the secondary fluid so that it would return to the boiler and not escape to the atmosphere.

d. Prime Movers and Working Fluids

As stated previously, the Rankine cycle consists of vaporization of a working fluid at an elevated pressure and expansion through one of a variety of prime movers. It is thus difficult to separate the research efforts as

found in the literature into separate classes of working fluids and prime movers. It will be shown that each prime mover is suited for a particular working fluid, range of power output and requirement of cost and complexity.

Since initial cost is such an important factor in selecting equipment for a fallout shelter, only the low-power devices that appear to offer a low first cost and a reasonable degree of complexity are considered. This eliminated many prime movers in which reheat cycles and various methods of pressure and velocity compounding were used.

The pertinent findings of several experimental investigations with Rankine cycle equipment is now presented. The references used in the study are presented in the appendix and noted in the text as a letter and numeral in parentheses.

#### d-1 Water as the Working Fluid

The literature contains numerous reports of applications of small-horsepower prime movers (reciprocating engines and turbines) in which the working fluid was water. Stationary reciprocating steam engines supplied the majority of the power needs prior to World War I. The early steam automobile (H1) usually was equipped with a reciprocating engine of less than 20 horsepower (which is about twice the power rating considered in this study) and many ingenious methods were used to achieve fast acceleration and rapidly heated boilers. The efficiency of these engines was not exceptional (a steam rate of 22 pounds per brake horsepower/hour was claimed for a large engine in a 1926 steam bus). These engines could have been built in larger sizes, and they would have been more efficient. A reduction of the size would have decreased the efficiency. This application was rapidly supplanted by the more efficient and adaptable internal-combustion engine until the intense interest in solar energy utilization emerged following World War II.

A quite complete description of the many patents on the use of solar energy for the production of power has been published (H4). The overall conclusion of the majority of the studies made may be stated as follows: The use of steam (produced in boilers heated by flat plate or low-cost focusing collectors) as a working fluid in low-power reciprocating engines cannot presently compete (even when using "free" solar energy) with the internal-combustion engine using expensive fuels. The wheel speeds of single-stage reaction or impulse turbines in a Rankine cycle (with only a small temperature difference between the boiler and condenser) are excessive, and expensive multiple wheel turbines cannot be tolerated. Clearly, some new ideas were considered to be necessary in this field.

Two papers (H5 and H6) were presented in which an attempt to reduce initial cost by use of low-pressure (55 to 65 psia) steam by means of a simple Hero-type turbine was made. The prime mover cost was estimated to be less than ten dollars, but the power output was only 0.17 hp at 3500 RPM and the thermal efficiency was approximately 1.0 percent. Several other small engines were tested (D slide-valve, poppet-valve, and an impulse turbine) during the investigation. The poppet-valve reciprocating engine (manufactured by a local firm headed by a steam-car enthusiast) gave a 4.5 percent thermal efficiency when used with 140 psia saturated steam. The engine was designed for approximately 10 hp using 800 psia steam.

The Army Engineering Research and Development Laboratories (ERDL, Fort Belvoir, Va.) sponsored a research program (H7 and H8) in which a 10 hp, in-line, 3 cylinder, single-acting, overhead-popped-valve, steam engine was to be located outboard of a reconnaissance boat, while a gasoline fueled, flash boiler was to be located inboard. Gasoline was flung radially in the combustion chamber and mixed with forced-draft air. The products of combustion passed over the flash tube to produce

1000° F., 1500 psia steam. The steam rate was predicted to be approximately 14 lb/Bhp hr. (with a 25 percent cutoff) and the unit was actually built and tested. No actual operating efficiency was reported for this unit.

d-2 Freon as the Working Fluid

The requirement of a quiet, portable, power generator for front-line troops led the ERDL to award a contract to the Battelle Memorial Institute in 1959, - (H9). A supercritical cycle utilized Freon 114 as the working fluid along with a rotary-vane expander as the prime mover, a gasoline burner, and a flash boiler. The design objective was to obtain a useful output of 6 hp with a fuel rate of 1.7 lb/hp-hr.

The project was fraught with difficulties. The rotary-vane expander (developed in cooperation with Vickers, Inc.) was suggested by previous experience with rotary-vane compressors in refrigeration work. Also, little success had been previously achieved with turbines. The first expander showed a vapor-flow rate higher than the design value, and the vanes formed ripples on the stationary surface. Tungsten carbide was used to reduce wear on the cam ring, but wear then occurred elsewhere. The hoped-for isentropic expander efficiency of 70 percent was actually 56 percent (with the condenser and inlet pressure lower than the design value).

The expander required that all surfaces be coated with a lubricant (fluoralkyl camphorate) because of the poor lubricity of Freon 114. The vapor generator developed hotspots during startup. Hence, it could not be determined if the excessive decomposition of the working fluid during the test was due to thermal decomposition or chemical reaction with the lubricant.

The unit was hermetically sealed except for the power shaft from the expander used to drive the alternator.

The use of magnetic coupling for a completely hermetically-sealed unit was discounted due to the requirement of portability. The total weight of the final laboratory unit (consisting of a condenser assembly attached to the main assembly by a flexible hose) was 318 lb. The net power output was 2.3 hp, and the fuel rate was approximately double the design value estimate.

Very little cost information was given in the study. However, one disadvantage of a supercritical cycle is evident. A costly regenerator was required to transfer heat from the highly superheated vapor leaving the expander to preheat the liquid Freon prior to entering the boiler. This cost should be reduced with a subcritical cycle if the exhaust vapor is nearly saturated.

The computed thermal efficiency presented in the Battelle report for a Freon 113 subcritical cycle (with a 350°F boiler and 170°F condenser) was 16.4 percent. This is slightly higher than the computed cycle efficiency for the same working fluid given as an example in Appendix 4.

Two studies (H10 and H11) (one experimental and one theoretical) in which Freons are used as the working fluid were found. The power ratings were 450 hp and 750 hp. A radial inward-flow turbine was used as the prime mover. The experimental effort made use of 850°F exhaust gas from a gas turbine to heat Freon 11. No thermal decomposition was reported. The theoretical (or design) study considered using Freon 114 in a hermetically-sealed turbine-alternator unit. Some apprehension was expressed concerning the windage losses in an alternator operating in Freon exhaust from the turbine.

It is clear that the radial inward-flow turbine is not the proper prime mover for low-horsepower units. This is confirmed by numerous accounts of these turbines (H12-H14) and will be discussed briefly.

The power rating for which the various turbines (axial-impulse, radial inward-flow, and axial-reaction) are most suited as prime movers is dependent on a familiar hydraulic term "specific speed" which is defined as

$$S = N \sqrt{Q/H^3}$$

where N is the turbine rotational speed  
Q is the volume flow rate of working fluid  
H is the drop in head across the turbine

This equation has been generally used in each analysis of radial inward-flow turbines, and it is accepted that the axial-reaction turbine is suited to large flow rates with small heads; the radial inward flow turbine is most suitable for average flow rates and rather high heads; and the impulse turbine (or even positive displacement machines) is most suitable for very low flow rates (as found in low horsepower machines) with high heads (such as that obtained with a heavy-molecular-weight working fluid). It may be of interest to note that light-molecular-weight working fluids are satisfactory for the positive displacement engines that extract expansion work from the working fluid, but heavy-molecular-weight fluids are desired for small turbines that extract kinetic energy from the working fluid since nozzle losses are reduced.

The range of power ratings in which the radial inward flow turbine is most suitable for gas turbines has been experimentally established to be approximately 20 to 500 hp, and the range for use in Freon systems has not yet been determined.

#### d-3 Monochlorobenzene (MCL) as the Working Fluid

Encouragement for solar workers concerned with solar energy utilization was recently reported (H18). Dr. Tabor of the National Physical Laboratory of Israel was familiar with a paper presented by

Dr. L. D'Amelio at the 1955 Tucson Conference on Solar Energy (H17) in which it was pointed out that the excessive wheel speeds encountered using water as the working fluid could be reduced if a heavy organic fluid were used. Hence, the working fluid could be used over a reasonable boiler-to-condenser temperature range of 200°F. or 300°F. with a simple, single-stage turbine.

Dr. Tabor and his colleagues examined many organic compounds (which did not include Freons) and arrived at the conclusion that MCB (more usually named chlorobenzene) offered the best combination of cost, stability, molecular weight, etc. Although the paper was primarily a theoretical study, an actual turbine-collector unit was demonstrated at the conference.

The device described by Dr. Tabor was an impulse turbine operating subcritically with partial admission (2 nozzles) for a small 2 KW unit, while the same housing and turbine wheel were used as a 10 KW unit with full admission (10 nozzles). The wheel speed was 18,000 RPM and a 6 to 1 gear reducer was used to reduce the speed and drive feedpumps and an electric generator. The study indicated that 35 percent of the developed power would be required to overcome friction in the 2KW unit, while only 10 percent of the developed power would be lost in the 10 KW unit. The computed full-load thermal efficiencies for the two units with a 350°F. boiler and an 86°F. condenser were 19.6 and 17.5 percent for the 10 KW and 2 KW units respectively. These efficiencies do not include collector efficiencies (nor combustion efficiencies for fossil-fuel-fired units).

A personal communication with Mr. Yellott of Yellott's Solar Laboratory indicated that the predicted efficiencies were realistic. Since only 3 of the 5 solar collectors were operating at the time of the demonstration, the power output was 5 hp (sun conditions were not given). A more recent paper by Dr. Tabor presented the unit as a 5 KW unit (F1); also plans are in progress for a fully integrated power system to be completed by late 1964.

e. Recommended Thermodynamic System

In view of the above survey of the current literature, our thermodynamic analysis, and the possibility of a sealed unit, it is recommended that development be undertaken for a novel auxiliary power system for fall-out shelter use consisting of a single-wheel axial-impulse turbine and a flash boiler (probably with a secondary fluid). The other components (feedpump, alternator, etc.) will require a more detailed investigation of commercially-available, reliable equipment. For example, the Battelle study indicated that an aircraft-quality 3600 rpm feedpump gave satisfactory performance. It would be more desirable to use small, high-speed, centrifugal feedpumps if they are available. They have been used successfully in larger waste-heat recovery systems (H10).

Ideally, a high-speed alternator enclosed in the turbine casing would be desirable if the friction losses due to the presence of a heavy-molecular-weight fluid would not be excessive. The higher alternator speed would result in higher frequency power output that would be satisfactory for lighting and could be satisfactory for motor operation. The motor operation might require some modification to the power output such as reduction in frequency or conversion to direct current, but it is possible that by increasing the voltage along with the frequency, a conventional motor could be used without modifying the frequency of the power output. The effects of the above changes would be to lower the starting torque and increase the power output. The increased power output probably would require additional cooling of the motor due to the increased frictional losses. Alternatives are the use of a gear reducer, or investigation of magnetic coupling techniques so that the alternator may be outside of the turbine casing.

The working fluid would definitely be a heavy organic material. The success with monochlorobenzene is encouraging as well as the success with heating Freons with low temperature flue products. Due consideration must be given to the storageability of the working fluid



as well as the decomposition rate due to infrequent operation of the equipment. The fact that MCB has low vapor pressure at room temperature may limit its storage life due to an air leakage.

The most desirable method of controlling the unit and making use of both liquid and solid fuels appears to involve fuel combustion in a Dutch Oven and passing the hot flue gases over the flash boiler. If the combustion process should become too rapid, the hot gases could be deflected from the boiler and wasted to the outside environment. Safety interlocks between this damper and the working-fluid pressure transducer should result in a reliable control.

f. Development of a Prototype System

The development of a prototype of a reciprocating or turbine system would require:

1. The basic system would be designed.
2. There are a number of components on the market that functionally could be used in the prototype, but some modifications might be required to integrate the components into the system. Therefore, the basic design would have to be re-evaluated in terms of this utilization of standard components.
3. A bread-board system for measuring the characteristic of the individual components would have to be built.
4. The components would be assembled in the prototype.

The estimated cost of a prototype reciprocating unit is \$20,000 and \$100,000 for a turbine unit. The estimate for the reciprocating unit is fairly good, but so much depends on the work that has to be done on the turbine rotor that the cost of developing the turbine is uncertain.

g. Potential Market

The promotion of the total energy concept (on site development of electricity and utilization of the waste

heat) by the gas utilities creates a sizeable potential market for these systems. However, it has to be recognized that the units have to be capable of functioning rather than being stored over a period of time for the total energy concept. The final design would have to be evaluated for life expectancy.

These units are stand-by power packs and could be marketed as such.

## 2. Stirling Engine

### a. Description

The Stirling cycle (I3) consists of an isothermal compression, constant volume heat addition, isothermal expansion, and a constant volume heat rejection process. The engines operating on this cycle have very high thermal efficiency (approximately 40 percent) due to the use of a regenerator. The purpose of the regenerator is to store some of the heat during the cooling process and return it to the gas during the heating process. A perfect regeneration process would give the Stirling cycle a Carnot cycle efficiency.

The mechanism of the existing Stirling engines is quite complicated in that two out-of-phase pistons are normally utilized. The mean effective pressure in the modern engines is approximately 1000 psi to improve heat transfer processes.

### b. Research Efforts

The Philips Company, Eindhoven, Netherlands began to apply modern knowledge of heat transfer to the Stirling engine prior to World War II. Their interest moved toward use of the cycle in the reverse direction with the result of a very efficient air liquefier. The General Motors Research Laboratories have been involved in the development of the engine in the United States (I3), while the Allison Division of GM is examining possibilities of using the engine in space satellites. A very recent paper (I4) has suggested that the engine be used in conjunction with a thermal storage means for the propulsion of a submarine.

The GM engine uses hydrogen for the working fluid with a mean pressure of 1000 psia, but helium has been suggested as an alternate fluid. The crankcase is atmospheric pressure; hence, the displacer-piston rod and the power piston require efficient seals.

A personal communication confirms the statement in the Battelle report that the ERDL is sponsoring research on a 3 KW engine-generator set using a Stirling engine for use as a quiet power source for reconnaissance missions.

c. Advantages

The Stirling engine is a quiet, efficient, power unit that may use a variety of fuels in a combustion chamber external to the engine. It has a high specific power rating (2 hp/cu.in. compared with 0.5 for a diesel engine).

d. Disadvantages

The Stirling engine is quite bulky (if the external combustion system is of any size), expensive (estimated at an excess of \$2,000.00 for batch production of a 3 KW unit), and not expected to store any easier than an internal-combustion engine. It is presumed that the working fluid would have to be stored separately and the engine would be charged prior to operation. Hence, preparation for storage after testing would be complicated.

3. Unconventional Internal Combustion Engines

Although there are several unconventional internal-combustion engines either in development or on the drawing boards today (J1 and J2), none seem applicable as a source of power in a shelter. The problems associated with the storage of gasoline and of the engines themselves will be the same as those encountered when considering conventional internal-combustion engines. The problems of the unconventional internal-combustion engines will be compounded by the unfamiliarity of the servicemen with these engines. Even though this is the case, a brief resume of each will be given.

a. Stratified-Charge Engine

A stratified-charge engine is the outgrowth of an idea which would permit the fuel-air ratio, which is approximately constant in conventional gasoline internal-combustion engines, to be varied from 1/16 to 1/50 or less. The efficiency of the engine would be higher, especially at light loads, if the engine could take in a full quantity of air at all times and the quantity of fuel could be varied. A homogeneous fuel-air ratio of less than 1/16 or 1/17 is too lean to ignite reliably, consequently, attempts have been made to develop "stratified-charge" combustion, in which an adequately rich fuel mixture (near the spark plug) is ignited first and the resulting heat and pressure burn the remaining, substantially leaner, mixture.

The advantages of stratified-charge engines include better fuel economy, ability to burn a wide range of fuels, the emission of fewer smog-producing residues, and lower compression ratios (hence less cost and weight than the diesel). Among its disadvantages would be the following: it is likely to be 25 percent more expensive and possibly 20 percent heavier and bulkier than conventional gasoline engines.

The problems associated with storing the stratified-charge engine and its fuel would be the same as those encountered with the conventional internal-combustion engines. A further disadvantage would be the unfamiliarity of these to servicemen.

Among the companies actively developing the stratified-charge engine are Texaco, Ford Motor Company and Southwest Research.

b. Wankel Engine

The major objection to conventional internal-combustion engines, the reciprocating motion of the pistons, is eliminated in the design of the Wankel engine. A three-sided "piston" rotates eccentrically within a specially shaped housing and is geared directly to the output shaft. A mixture of gas and air in the engine chamber

is compressed and then fired by a single spark plug. The three apexes of the "piston" always touch the walls of the combustion chamber. This creates three spaces in the chamber which constantly vary in size to complete the operations of a cycle. If the problems of sealing, high wear rates and other technical difficulties can be overcome, the Wankel engine may become competitive with the conventional internal-combustion engine. The basic simplicity of the Wankel engine offers substantial savings in manufacturing cost, weight and bulk and it should be smoother in operation and costs less to overhaul than conventional internal-combustion engines. Its disadvantages are that its life will be shorter, fuel consumption greater, and its smog-creating residues slightly greater.

At present Cals-Wright is developing Wankel engines in sizes about 100 horsepower. Before production models are available, much testing will have to be accomplished. These tests will include the determination of the best compression ratios, best position of the spark plug, best fuels, multi-piston systems and improved sealing.

If this engine were available for fallout shelter applications, the fact that its fuel consumption is expected to be greater than conventional internal-combustion engines may not be significant since the period of use in a shelter is expected to be short. The fact that there are only two moving parts is attractive, but its novelty, when developed, would make it a "stranger" to the servicemen who would maintain it. Fuel storage problems would be the same as those associated with the conventional internal-combustion engines.

c. Free-Piston-Turbine

The free-piston-turbine compound engine is remarkably simple mechanically, which should in principle make for low production costs and easy maintenance. It has excellent torque-speed characteristics and good fuel economy at full load. At light loads, its fuel economy is poor.

As in the two-stroke diesel, combustion occurs by compression ignition. The combustion gases from the gasifier section expand through the turbine. The combined air compression and diesel pistons are not attached to a crankshaft. Fallout shelter use, when power requirements are relatively small, would make application of the free-piston-turbine impractical. Units of 1000 horsepower are commercially available, but units below 80 horsepower were not found in the literature search. The Free Piston Development Company (Canada) is presently engaged in developing 80 to 200 horsepower units. The applications of the free-piston-turbine engine seems restricted to locomotives and marine propulsion. The storage of fuel and the engines themselves would further prevent their use in shelters.

d. Hybrid

A hybrid engine is a highly refined modification of the two-stroke cycle engine. The improvements over the conventional two-stroke cycle engine which would be incorporated in its manufacture would include the pressurizing of its lubrication system, the replacement of the crankcase and piston blower with a low cost positive-displacement rotary blower, replacement of the carburetor with direct-into-the-cylinder, timed, fuel injection and the introduction of stratified charge combustion. The first three changes would significantly improve the competitive position of the two-stroke cycle engine. It would be comparable to the conventional four-stroke cycle in most respects, but would be superior in terms of weight and bulk. The introduction of the stratified-charge combustion, however, presents the greatest, as well as the only completely new, developmental change.

The hybrid engine, if developed, could compete with conventional internal-combustion engines. Little is known of its storageability since it is still in the development stage. The size of these engines (greater than 50 horsepower) is larger than those which would be suitable as the prime mover for power supplies for fallout shelters. The applications for hybrid engines which looks most promising are in either automobiles or outboard motors of 50 horsepower.

e. Selwood Orbital Engine

The Selwood orbital engine has its pistons and cylinders orbit as part of a motor block around a stationary shaft. In effect, it is a revolving engine, hence it makes exhaust manifolding impractical. Another disadvantage is that it must be supercharged, as there is no inherent crankcase compression. The application of this engine in a shelter is also doubtful. Much research will have to be done before it is even seriously considered as a competitive engine. In fact, it seems as though it will continue to remain a curiosity. The connecting rods and crankshaft are not eliminated, but replaced by a series of parts which are inherently more complex and costly. Even if this engine were available, its utilization as a power supply in a shelter would be doubtful. Again, its storage and that of the fuel offers nothing better than the conventional internal-combustion engines. The impractical exhaust manifolding further limits this engine.

D. Fuels

1. Nuclear Fuels and Radioisotopes

The utilization of these fuels is discussed in detail in Appendix 2. The data may be summarized by saying that there are safe reliable means for generating heat by nuclear means to supply energy to Carnot-cycle limited energy-conversion devices such as closed cycle turbines, thermoelectric elements, thermionic diodes, etc. However, the use of reactors and isotopes is prohibitively costly and the supply of radioisotopes is too limited for wide-spread usage.

2. Chemical (Fossil) Fuels

a. Solids

a-1 Coals and Coke

i. Classification

Anthracite This is a hard, dense coal which does not produce dust on handling, but is somewhat difficult to ignite. Upon burning, it produces a clean fire with little ash. Its calorific value is high (14,250 Btu/lb.).

**Bituminous** This includes many types of coal which vary considerably in composition, properties, and burning behavior. The volatile matter varies from 18.7 to 40.8 percent and the moisture content from 2.2 to 26.9 percent. Their calorific values vary from 9,180 to 15,240 Btu/lb.

**Lignite** This coal has the highest moisture content (39.1 percent); the volatile matter is 29.5 percent and the calorific value is 7,400 Btu/lb.

**Cokes** The properties of cokes depend on the type of coal from which they are produced. A typical heating value is 14,500 Btu/lb.

ii. **Storage Characteristics**

Coals and coke store well. The main difference in storage characteristics is the tendency towards spontaneous combustion. Anthracite coals have the least tendency while bituminous coals have less tendency for spontaneous combustion than lignite. The property in cokes is a function of the coal from which they were prepared. Anthracite coals, bituminous coals and cokes are recommended for shelter application. Coals lose part of their heating value during storage due to the sublimation of some of their volatile material. The loss recorded by some investigators is at a rate of 0.5 to 1 percent per annum. A 5.5 percent loss in three years has been reported in one case. The loss rate of heating value is much less for coal stored in confined unvented places.

The volume which will be occupied by solid material varies from 50 to 100 percent of the storage space depending on the shape of the coal and the position assumed during filling.

The specific volumes of coals and coke are approximately as follows:



Anthracite Coal ..... 37 cu. ft./ton  
Bituminous Coal ..... 45-41 cu. ft./ton  
Coke ..... 100-90 cu. ft./ton

iii. Storage Precautions

The use of the following precautions against spontaneous combustion should be adequate to insure the proper storage of coal.

- a) Store in a confined (unvented) space.  
Avoid air drafts through the coal or coke.  
  
Do not store freshly mined coals. Coals should age six months before placing them in the storage bin.
- c) The storage area should be isolated from heat sources. For instance, do not store near boilers in an existing building.
- d) Do not mix coals in a bin. Use one bin for a anthracite coals, another for bituminous coals, etc.
- e) Avoid contamination of the coal by vegetable materials, rags, oil and other combustible organics.
- f) Store coal or coke that is considered uniform in size. Do not store coal that has a large percentage of fines.
- g) Do not store wet coal in a waterproof bin. Coal often contains pyrite, which reacts with water to liberate heat.

iv. Storage Inspection

Coals and cokes become more stable upon aging. If spontaneous combustion is to occur,

it will be indicated by a temperature rise in the first two years. This temperature rise could be detected by driving a hollow rod into the bottom of the bed and measuring temperature with a thermometer or thermocouple. As long as the temperature remains below 100°F., the coal would be safe. A decrease in temperature would indicate that the coal has passed its critical point and was stabilized.

v. Emergency Measures

In the event of excessive heating or spontaneous combustion, the coal or coke could be flooded with water, or dry ice could be placed upon the top of the pile. The dry ice would liberate gaseous CO<sub>2</sub> to replace the oxygen, and thereby stop combustion.

a-2 Wood

i. Classification

The major variable in wood is moisture content. Wood with more than 30 percent moisture is considered wet. Freshly cut wood contains 30 to 50 percent moisture, while one year old dried wood contains 18 to 25 percent moisture.

The various types of wood are composed mainly of approximately 50 percent carbon, 43 percent oxygen, 6 percent hydrogen, while the rest is ash and nitrogen. The heating value of dry wood ranges between 8,300 and 9,130 Btu/lb.

ii. Storage Characteristics

Wood is safer to store than coal because there is no problem of spontaneous combustion.

iii Heating Value

A cord of wood is a 4 by 4 by 8 ft. pile and contains the following percentages of solid material:

Timber cords	74.07%
Firewood cords (diam. over 6 inch)	69.44%
Bellet cords (diam. over 5")	55.55%
Brushwood cords (diam. less than 3")	18.52%
Roots	37%

Typical heating values of various woods are given in Table 1.

Table 1. Heating Value of Woods

<u>Type</u>	<u>Weight (lb/cord)</u>		<u>Heating Value (Btu/lb.)</u>		<u>Equivalent wgt. of 13,500 Btu/lb. Coal</u>	
	<u>green</u>	<u>Air-dried</u>	<u>green</u>	<u>Air-dried</u>	<u>green</u>	<u>Air-dried</u>
Ash, white	4300	3800	4628	5395	0.343	0.400
Beech	5000	3900	3740	5359	0.292	0.397
Birch, yellow	5100	4000	3804	5225	0.282	0.387
Chestnut	4900	2700	2633	5778	0.195	0.428
Cotton wood	4200	2500	3024	6000	0.224	0.444
Elm, white	4400	3100	3591	5710	0.266	0.423
Hickory	5700	4600	4053	5391	0.300	0.399
Maple, sugar	5000	3900	4080	5590	0.302	0.414
Maple, red	4700	3200	3745	5969	0.277	0.442
Oak red	5800	3900	3379	5564	0.250	0.412
Oak white	5600	4300	3972	5558	0.294	0.412
Pine, yellow	3100	2300	7097	9174	0.526	0.680
Pine, white	3300	2200	4226	5864	0.313	0.434
Walnut, black	5100	4000	4078	4650	0.302	0.344
Willow	4600	2300	2370	5870	0.176	0.435

a-3. Other solid fuels

Several data for other possible solid fuels are given in Table 2.

Table 2. Heating Value of Miscellaneous Fuels

<u>Fuel</u>	<u>Approximate Density (lb./ft<sup>3</sup>)</u>	<u>Approximate Higher Heating Value (Btu/lb.)</u>
Sawdust Briquets	75 - 80	8100
Straw	-	6000
Corn	-	8000
Cottonseed Hulls	15	7100
City Refuse	40 - 44	8800
City Rubbish	5.5 - 7.5	-

b. Liquids

b-1. Fuel oils

1. Classification

Fuel oils are mixtures of hydrocarbons. They vary mainly in volatility and in viscosity. These two properties affect the burning performance of each of these fuels. The fuel oils which may be applied as fuel to a small boiler with minimum handling and burning troubles are Nos. 1 or 2.

11. Storage

Light fuel oils (e.g., Nos. 1 and 2) are preferably stored in steel tanks and not in concrete or masonry tanks. Storage of these oils for long periods of time results in gum formation in the tanks, but this could be

decreased to the minimum by storing special-quality fuel oils.

Careful handling of the fuel oils is necessary in order to keep them free from moisture and dirt which contribute to the gum formation process.

If the piping connections are properly located in the tanks and the tanks are provided with duplex-type strainers, possible harm to an engine due to gum which may form in the tanks can be minimized.

The storage space required for liquid fuel oils is equal to 0.134 cu. ft./gallon.

The most suitable fuel-oil-feed system for simplicity and low initial cost is the Gravity-Feed System.

Storing fuel oils, especially the light grades, in atmospheric-vented tanks results in evaporation losses. These losses are directly proportional to the surrounding ambient temperature. Accordingly, these losses are expected to be low for buried tanks (less than approximately 0.2 per cent per year). Sealing the tank without vents during storage will eliminate this loss.

#### iii. Combustion

Complete combustion of fuel oils depends largely on the use of an adequate oil burner suitable for the type of fuel used.

The light fuels (Nos. 1 or 2) will permit the use of almost any simply-designed burner without any need for preheating the fuel to lower its viscosity.

The heating values of No. 1 and 2 fuel oils are 136,000-139,000 and 139,500-140,500 Btu/gal. respectively.

b-2. Gasoline and alcohols

Gasoline and alcohols could also be used as fuels. They store sufficiently well for combustion in burners, but their utilization is considerably more hazardous than that of the fuel oils. The cost is also somewhat higher. Therefore, they were not investigated in detail for this shelter application. Gasoline is treated in detail in Appendix 2 and in a concurrent project (A9).

c. Gaseous fuels

c-1. Liquefied petroleum gases

1. Types

The well known liquid petroleum gases are propane and butane. The former has a boiling point of  $-4^{\circ}\text{F}$ , while the latter has a boiling point of  $32^{\circ}\text{F}$ .

11. Storage

These gases have higher heating values (Btu/lb.) than the heavier petroleum fuels; also the actual storage volume will be comparatively small. They will have to be stored under pressure and auxiliary equipment is necessary to effect their evaporation before the gases reach the burner.

111. Combustion

Efficient burning of both butane and propane with the proper burners does not require specialized operating skill. They are used for home cooking and heating appliances.

c-2. Natural gas

Since the critical temperature is  $-82^{\circ}\text{C}$ , the long-term storage of the liquid is impractical (cryogenic storage). Storage at high pressure gas would require expensive tanks.

c-3. Producer gas

Producer gas (hydrogen and carbon monoxide) has been used in Europe and Japan for use in automobiles. It is generated by the incomplete combustion of combustible solids such as wood, charcoal, and coal. Gas producers will be covered in greater detail in the final report of a concurrent project (a9)..

c-4. Acetylene

Acetylene can be generated by the reaction of water and calcium carbide. Commercial units are available for this operation. However, the cost per Btu generated has caused this gas to be eliminated from further consideration.

E. Combustion Equipment

The information presented here is to aid in the visualization of the process and equipment rather than to supply complete engineering details. In general, the equipment has already been engineered and in most cases is commercially available. Chimneys are the exception, and design information is presented.

1. Combustion of solid fuels

a. Coal and coke

Anthracite coal burns very well leaving little ash, but it is difficult to ignite. Firing of most bituminous coals requires manual removal of the ash in clinker form. It is standard practice to have a grate area large enough to allow for an 8-hr. firing period plus a 20 per cent reserve for igniting a new charge.

The time required to burn 1 lb. of coal per sq. ft. of grate area with a natural draft of 1/8 - 1/2 inch water gauge is as follows:

<u>Type of Coal</u>	<u>Grate Area</u>	
	<u>Up to 14 sq. ft.</u>	<u>14 to 45 sq. ft.</u>
Anthracite:		
Buckwheat	3-4 hr.	4-5 hr.
Pea	5-5 1/2 hr.	5 1/2-6 hr.
Nut and Larger	8-10 hr.	10-13 hr.
Bituminous	9.5-12 hr.	12-15 hr.



The usual furnace heat release rates are as follows:

Refractory furnace	15,000-30,000 Btu/cu.ft.-hr.
Water-cooled furnace	30,000-45,000 Btu/cu.ft.-hr.
Spreader stoker	25,000-35,000 Btu/cu. ft.-hr.
Single retort stoker	30,000-40,000 Btu/cu.ft.-hr.

Typical boiler efficiencies with hand firing of coals are as follows:

Bituminous coals----	43 - 67%
Anthracite coal-----	57 - 69%
Coke-----	75 - 76%

b. Wood

The efficiency of wood burning depends much on the condition of the wood, the degree of dryness, its size and uniformity. Hence, a dry wood, cut uniformly in small pieces, would give good burning results. If the moisture content is more than 55 per cent, combustion becomes difficult to maintain unless other fuel is burned with it.

The Dutch Oven type furnace is the most suitable type of furnace for burning wood. It has to be designed so that the refractory walls and arches provide maximum radiant heat reflection in order to dry the wood and maintain gasification and combustion.

Standard practice dictates that approximately 1 sq. ft. of grate area be available for each 35-50 sq. ft. of boiler heating surface.

The burning rates for wood are 20-35 lbs. (dry wt.) per sq. ft. grate/hr. with auxiliary fuel and 35-50 lbs. (dry wt.) per sq. ft. grate/hr. without auxiliary fuel. Usual furnace heat-release-rates for wood burning are approximately 10,000-15,000 Btu/cu.ft. of furnace volume. This rate may be increased to 25,000 Btu/cu.ft.

of furnace volume with drier wood and the use of water cooled walls.

The furnace height should allow an adequate distance (about 1 ft.) between the furnace roof arch and the apex of the cone-shaped pile of wood on the grate.

Approximately 80 percent of the combustion air passes over the fuel; the remainder passes through the fuel bed. The excess air is normally 30-40 percent.

A typical boiler efficiency with wood firing is approximately 60 percent. This may reach 75 percent with preheating of the combustion air and the use of dry wood.

## 2. Combustion of Fuels Stored as Liquids

### a. Fuel Oil

Success in burning fuel oil depends on having a suitable burner, a combustion chamber of the right shape and dimensions and the correct design of the boiler and furnace.

The oil burners could be divided into the following classes: the air aspirated type, mechanical atomizing type, and the vaporizing pot type.

The most appropriate type of burner for operation without any driving power is the vaporizing pot type. This type works satisfactorily with distillate-type fuel oils (i.e., Fuel Oils Nos. 1 and 2). Effective burning of these low-viscosity, high-volatility Fuel Oils could be achieved by the simplest type of burner like the ones used in the past for the steam automobiles. Low viscosity fuels flow satisfactorily to the burners under a gravity head of approximately 10-15 ft.

The hourly heat-release rate in a furnace fired with an oil burner ranges from  $20-45 \times 10^6$  Btu/cu.ft.hr. of furnace volume. The lower limit could be assumed to be a safe limit for continuous operation in a solid-refractory-walled furnace.

The efficiency of oil-fired boilers is approximately 70-80 per cent.

For most efficient utilization of fuel it is necessary to 1) obtain nearly complete combustion (maximize the  $\text{CO}_2$  and minimize the  $\text{CO}$ ) and 2) secure the lowest practicable outlet flue gas temperature at the chimney base.

Fuel oil is mainly composed of carbon and hydrogen; consequently, the products of combustion are  $\text{CO}_2$  and water vapor accompanied by nitrogen from the combustion air. The theoretical percentage of  $\text{CO}_2$  in flue gases of petroleum oils, burning without excess air, ranges between 15-16 per cent.

b. Liquified petroleum gas

The main types of L.P.G. burners are the atmospheric and the power types. Both types of equipment are available from a number of manufacturers and could be used for the shelter application. The American Gas Association, as well as gas appliance manufacturers, have considerable experience in tailoring burners to specific needs. Burners could be easily obtained for the shelter application.

3. Chimneys

a. Natural draft

The short permissible stack heights for the shelter application makes the use of natural draft chimneys difficult but by no means impossible.

The literature search showed several methods for calculating chimney characteristics, but all the methods yielded approximately the same results. The maximum draft that can be developed is about 0.1 in.  $\text{H}_2\text{O}$  gauge.

The low stack-height restrictions on the shelter application cause the use of conventionally designed equipment to be questionable. However, if the possibility of designing an over-all system (air intake, grates, fuel firing procedure, draft control, and chimney) specifically for the shelter was considered, the probability of designing a satisfactory system is very

good. The engineering principles are known, but the development (due to the unusual problem) would have to be a combination of experimental work and calculations. A good starting point for such an investigation would be to consider the use of coke plus a manually-operated blower to aid in the ignition of the fresh charge.

General information on various draft requirements are given in Table 3.

**Table 3. Drafts Required by Typical Residential Heating Devices or Appliances**

Device	Draft (inch water)	Stack Temp. (°F) (a)
Space heater, oil burn. g,	0.06	1,000
pot burner		
Warm air furnace, oil burning,		
pot burner	0.06	860
Warm air furnace, hand fired	0.06 (c)	900
Floor furnace, oil burning,		
pot burner	0.06	860
Mechanical oil burner 5 g.p.h.	0.03 (b)	---
Mechanical oil burner 5 g.p.h.	0.05 (b)	---
Cooking stove, solid fuel	0.04 (c)	400
Space heater, coal burning	0.06 (c)	900

- (a) 18 inches from heater
- (b) draft in firebox
- (c) chestnut sized anthracite

The material of construction for the chimney does not have much effect on the draft produced. Table 4 presents performance as a function of cross-sectional area of the chimney.

**Table 4. Chimney Performance**

Nominal external dimensions (inch)	Internal area of liner (inch <sup>2</sup> )	Flue Gas Temp. at chimney inlet					
		200	600	1000	200	600	1000°F.
		Mass flow rate (lb. /hr)			Flue gas velocity at chimney inlet (f.p.m.)		
9 diam.	38.5	130	150	170	175	250	300
9 x 9	49	215	306	334	175	400	600
12 diam.	78.5	290	320	320	150	---	---
9 x 13	77	295	320	320	150	---	---

These results were obtained with clean chimneys.

Wind has a deleterious effect on the operation of short chimneys because of the relatively low available draft. Downdraft has to be avoided by proper construction of the chimney top with respect to surrounding buildings, wind direction and speed, as well as by the possible use of a suitable chimney cap. A positive pressure as high as 0.1 inch water gauge is encountered in certain cases.

In order to prevent loss of draft, the length of the smokepipe between the furnace and chimney should be as short as possible. Also, air leaks should be avoided in the smokepipe and chimney; this may involve the elimination of dampers. Insulation of the smokepipe also aids in increasing draft.

b. Forced Draft

Forced draft systems will work for utilization in a shelter. The problem is to design the draft system to fit the application. The American Gas Association has several manuals for friction losses in ducts. This data plus the pressure losses occurring in the equipment itself could be used in the design for these devices.

F. Heat Rejection Equipment

The rejection and utilization of rejected heat from the shelter is discussed under a concurrent project (A9). However, recognizing that current generator sets are designed solely for the purpose of electric power generation, Appendix 5 discusses modifications for the shelter application. These modifications are only suggested improvements. They could be, but have not been, developed through a research program.

The following discussion of the heat rejection equipment is to present some of the background material for evaluating the various means of cooling.

1. Air Cooling

Heat rejection utilizing the mass flow of air and the ultimate rejection of the air to the atmosphere is feasible for some types of shelter operation. Therefore, a discussion of the advantages, disadvantages, and means for compensating for the disadvantages is included in this section.

Air cooling the internal-combustion engine would eliminate the liquid cooling system. Some Carnot cycle limited devices could have the working fluid and cooling fluid be the same liquid by placing the condenser outside the shelter. A factor in favor of air cooling is that even though the manufacture of engine-generator sets may be considered limited production, the engines used in these sets are mass produced since they are also used in other applications. The majority of these small engines are air cooled, and restriction of the engines to water-cooled types could considerably decrease the source of these devices.

A disadvantage of the air-cooled method is that once thermal energy is imparted to the air, the low heat-transfer coefficient of air tends to increase the difficulty of reclaiming this thermal energy at high temperature for other shelter applications. However, there are still means for utilizing this heat if the shelter food supply is only to be warmed, i.e., small individual containers of food could be placed in the hot air stream. While this warming procedure has not been studied in any detail, it is apparent that it could have some sanitary advantages and might allow a better matching of the quantity of food consumed to the quantity heated by untrained personnel.

The large amounts of cooling air normally required for cooling the energy-conversion device is recognized (approximately 30 times the combustion air requirement). This air may be partially used for other combustion processes, e.g., gas-fired absorption refrigeration and high temperature cooking equipment.

This may aid in reducing the required electrical load on the shelter power system if the necessary auxiliary equipment is available. Consider the following example:

- a. Suppose that 60,000 Btu. of air conditioning were desired.
- b. Assuming a coefficient of performance of 3.0 for a vapor-compression air conditioner, 20,000 Btu. of electrical energy would be required  $(60,000/3)$ .
- c. Assuming a 10% over-all thermal efficiency for electric power generation for a Rankine cycle device, and 15% for an internal combustion engine, the chemical energy requirements would be 200,000 Btu. and 133,333 Btu. respectively.
- d. Assuming that a small gas-fired absorption unit a coefficient of performance of 6.5 were available, the chemical energy requirement would be reduced to 120,000 Btu (40 percent reduction for the Rankine-cycle generator set, but approximately 10% for the internal combustion engine-generator set).
- e. The gas-fired unit would also reject 30,000 Btu  $(120,000/4)$  from the boiler of the absorption system at a high temperature. This energy may then be used for other shelter applications, e.g., cooking, washing clothes and sterilization requirements.

## 2. Liquid Cooling

Heat rejection by liquid cooling from the chemical-to-electrical energy-conversion device may provide heat which is satisfactory for warming food. Liquid cooling does not require the high mass flow rate of air through possible blast valves and filters as it enters the engine room, but the thermal energy must be eventually rejected to the atmospheric air. This would imply that

some means is required for circulating air past the outside condenser if the natural wind velocity is not sufficient. Hence, the main advantage of liquid-cooled engines is that the cooling air (which may be contaminated) does not have to enter the engine room.

3. Evaporating-Condensing-Vapor Cooling

This mode of heat removal is discussed in detail in Appendix 6. It is essentially a tubular configuration which allows a liquid to evaporate at the bottom of a hermetically-sealed chamber and to condense at the top. The functional characteristics are similar to a circulated liquid system, except that a pump is not required and heat flow is always upward (hence, the device is often called a "thermal diode").

4. Combination Cooling Devices

A system that circulates air over the energy converter, past a liquid-cooled heat exchanger or an evaporating-condensing-vapor heat exchanger, and back to the converter could be used. The penalty for the use of this system would be an additional heat exchanger in the heat rejection system. Also, air could cool the power converter and be rejected directly to the atmosphere as it becomes available from the rest of the shelter. If the major fluctuating electrical load was to provide power for the air-supply equipment for the shelter, this heat rejection means would have the greatest capacity when it was needed most. This system would have the advantage of both the air and liquid cooling systems.



#### V. CONCLUSIONS AND RECOMMENDATIONS

The internal-combustion-engine-generator set is mass produced and its functional characteristics are well known. Experience with these units to operate compression systems for refrigeration of truck trailers gives background for operating the units in a confined space. Consequently, this unit would be the easiest to install in a shelter without further research. However, this system has two obstacles that have not been sufficiently studied to allow it to be selected as the ultimate unit for shelter utilization.

These two obstacles, the short storage life of gasoline and the current need for periodic exercising of the engine, could safely be overcome by replacing the fuel supply every six months and exercising the engine for one-half hour each week. Hence, if it is necessary to install chemical-to-electrical power conversion equipment in shelters immediately, (without further research) the engine-generator set has the greatest proof of reliability and would be chosen. Familiarity of the "man on the street" with this system should also be recognized.

The procedure of replacing stored gasoline and exercising the engine is costly, requires considerable attention, and if not done could lead to unavailability of the system when needed. Therefore the following research programs are recommended:

##### A. Investigate the Cold Storage of Gasoline

When gum is present in gasoline it can clog small orifices such as those present in the carburation system of a gasoline engine and render the engine inoperative. The heating value and volatility of a properly stored gasoline would not change appreciably during storage. The problem of storing gasoline is basically one of preventing gum formation during storage. This gum formation can be retarded both by additives and the use of straight run gasoline as contrasted to catalytically cracked gasoline. However, there are limitations which do not allow the improved purity or extra additives to extend the storage life of gasoline indefinitely. Two years storage life at room temperature was the longest time estimate that was obtained for storage of a gasoline that would be specifically tailored for shelter use. It was suspected that the gum formation, which is due to chemical reaction, would be less at lower temperatures and consultation with personnel of several oil companies qualitatively confirmed this guess.

Current estimations for Contract No. OCD-OS-62-282 on engine-generator sets, indicate that regular good quality gasoline can be stored for ten years at 32°F and more than 50 years at 0°F without serious gum formation. However, this study, which is a small portion of the above project, is limited to estimates based on theoretical information and confirmed experimentally for substances other than gasoline. These results should be confirmed by experimental data on various gasolines.

Kerosene, or No. 1 fuel oils will, in general, store better than gasolines, and liquified petroleum gas will store better than kerosene or No. 1 fuel oil, but we could find no guarantee that these materials would store up to five years at room temperature. It should be emphasized that storage for these lengths of time simply have not been studied. Therefore, in view of the scarcity of diesel engines as compared to gasoline engines, and the anticipation of satisfactory old storage results for gasoline, it is recommended that cold storage tests be conducted on gasoline. The fact that the general populace has more knowledge of gasoline-fueled engines than diesels or liquified-petroleum-gas-fueled internal-combustion engines influenced this recommendation.

We are aware of data that indicates that high grade gasoline has stored well at room temperature, but the extrapolation factor ( [desired life expectancy - time lapse since start of test] / time lapse since start of test ), which is a measure of how far data must be extrapolated to suit the 10 year requirements, indicates that the cold storage tests should be started as soon as possible. It is, therefore, recommended that cold storage tests (with room temperature control samples) be started immediately on the various available gasolines with and without commercially available additives.

**B. Investigate the Long-Term Storage of Internal-Combustion Engines**

All manufacturers of small engines and engine-generator sets that were contacted favored weekly exercising of the engine. This exercising is being considered in Contract No. OCD-OS-62-282.

The possibility exists, using modern engine packaging procedures, for storing an engine generator set for 10 years. However, techniques have to be developed and tested.

Factors such as the damage of an engine during shipment and on-location testing need to be considered. Theoretical data has to be supported by experimental evidence.

**C. Investigate Turbines Using a High-Molecular-Weight Organic Working Fluid**

The hermetically-sealed impulse-turbine-generator set has most promise for becoming the ideal shelter power-generator set below 10 KVA. Its advantages are good storage characteristics, possibility of intermittent use for on-site testing without subsequent elaborate repackaging, ability to utilize low cost fuel with good storage characteristics (wood, coal, or coke), and a potentially-low initial cost. The high-molecular-weight organic working fluid is necessary to insure reasonable wheel speed.

The area to be investigated is the turbine design and the possibilities of using an existing turbine; the design and building of a proper type flash boiler, possibly using a secondary fluid; and the design of a heat-rejection system that is consistent with shelter requirements.

The procedure should be to build a full-scale breadboard system for evaluating the functional characteristics of the individual components and the integrated system. Then the system should be incorporated into a semi-portable, hermetically-sealed package.

**D. Investigate a Reciprocating Steam Engine Using Water as a Working Fluid**

A reciprocating steam engine does not have a wheel speed problem. Therefore, it can use water as a working fluid. The expected efficiency would be low (around five percent), but the inefficiency could be partially off-set by utilization of the waste heat. An air conditioner, using heat as the energy source, could be one possibility. Small heat consumption loads such as cooking would not be considered sufficiently large to be able to off-set the inefficiency.

The development of a hermetically-sealed unit for 10 years storage would be difficult, but the problem would not be as great as for an internal-combustion engine in that on location testing would not result in products of combustion entering the engine. The unit could also use fuels with good storage characteristics such as coal and coke.

E. Observe Progress in Fuel Cell Development

Considerable work is being done on fuel cell development. The state of the art is such that the progress towards using these devices in shelters will probably not be appreciably accelerated by anything but very high expenditures. Reviewing fuel cell development until more basic data is obtained by fuel cell developers appears to be a logical procedure.

The fuel cells have a heat rejection problem due to inefficiencies and in this respect have problems similar to the other internal-combustion devices, and they also have the fuel-storage problem. These problems are discussed in (A9). However, the higher efficiencies of fuel cells tend to minimize the problem. See Appendix 1 for data on specific cells.

F. Engineer Accessory Equipment

The design of economical accessory equipment such as combustion chambers, boilers, heat removal means, and means for removing waste products is an engineering problem in obtaining the most economical design. These factors are discussed in (A9).

1. Boiler and Heat Source

Use a flash boiler equipped with a suitable combustion chamber and burner for reciprocating steam engines. Low initial cost is the principle factor. Use of an indirect-fired flash boiler (contains a secondary fluid) is recommended for heating high-molecular-weight organic fluids for small turbine-generator units. Localized hot spots can cause thermal decomposition in small direct-fired boilers.

2. Heat and Waste Product Rejection Systems

Forced draft, circulating-liquid, and evaporating-condensing vapor devices need to be tailored to fit the specific electric-power generating system. Natural-draft chimneys (thermal gradients) also have to be designed to meet the low stack requirements of the shelter. These devices need to be tested by prototype building.

## APPENDIX 1 FUEL CELLS

SECTION 1 H<sub>2</sub>-O<sub>2</sub> Fuel Cells

These cells are of interest because the waste product is water. Thus far the water is contaminated, and unsuitable for drinking without purification. Water purification is discussed in appendix 5 for purifying water from engine generator sets. A similar scheme appears feasible for fuel cells.

The cells have the potential of being reliable for the only moving parts would be valves and pumps.

The waste products are not toxic in the sense that they would not pollute the shelter atmosphere.

Their idling fuel consumption is extremely low.

A condensed summary of the aero-space system, is below:

H<sub>2</sub>-O<sub>2</sub> Fuel Cells for Aero-Space Applications

Currently only two kinds receiving much attention;

General Electric

GEMINI SYSTEM - low current density, light weight

Operates at 140°F.

Ion exchange membrane electrolyte

Pt catalyst on both sides

Titanium Electrodes

Produces up to 2Kw

Produces ~ 1 lb of water/Kwhr, at energy efficiency of 50-60%

Cell potential ~ 0.7v

Current densities ~ 40 amp/sq. ft. (~ 43 ma/cm<sup>2</sup>)

Have operated for ~ 1000 hours in assemblies

Have operated for ~ 5000 hours as single cells

Moving parts - check valves to control gas flow  
pump to circulate coolant

## Problems

1. membrane failure, punctures caused by current collector screens
2. failure of cell assembly adhesives
3. poor contacts between membrane and electrodes
4. water contamination
5. gradual degradation of performance with time of operation

Pratt-Whitney

APPOLLO SYSTEM - high current density, lighter voltage, weight more  
 Operates at 500°F (1-5 atm)  
 85% KOH electrolyte  
 Cathode: "lithiated" nickel oxide } both sintered, porous structure  
 Anode: nickel  
 Cell potential, greater than 0.9v  
 Current densities ~200 amp/sq. ft. (~215 ma/cm<sup>2</sup>)

## Problems:

1. electrolyte leakage thru seals
2. vibration troubles
3. pump failures
4. electrode manufacturing difficulties
5. startup procedures more complicated because of temp.

For both systems, the investigators are very optimistic; and foresee no difficulty in overcoming the problems, so that the cells will be available for these aero-space applications.

However, very recent reports (Milwaukee Journal, Sunday Dec. 8, 1963) indicate that neither the Pratt-Whitney nor General Electric Systems are anywhere near operational, and that NASA may be looking elsewhere for other approaches.

## SECTION II Hydrocarbon Fuel Cells

Very recent advances indicate that a reformer operation to liberate hydrogen from the hydrocarbon is not necessary. These new hydrocarbon fuel cells are discussed below:

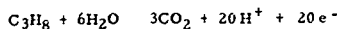
Up to now, fuel cells capable of burning hydrocarbon directly to water and carbon dioxide have not been particularly successful. Generally, high temperatures have been required, and efficiency has been very poor. The few attempts to utilize temperatures below 100°C have required the use of concentrated H<sub>2</sub>SO<sub>4</sub> electrolyte, platinum electrodes, and have produced only 10-20 ma/cm<sup>2</sup>, and at very low potentials. Thus these electrode systems have not been considered to be feasible as the basis of practical fuel cells.

Two very recent reports, however, have announced a new approach which may eventually lead to a practical hydrocarbon fuel cell. These reports:

1. Oswin, H. G., A. J. Hartner, and F. Malaspina  
Nature, 200, 256B (1963)
2. Grubb, W. T., and L. W. Nicdrach  
J. Electrochem. Soc., 110, 1086 (1963)

announced that propane can be oxidized rapidly at a platinum anode, using 14.6M phosphoric acid as the electrolyte. The first group, working at

Leesona-Moos Laboratories, reported current densities up to 200 ma/cm<sup>2</sup> at 220°C, while the second group obtained up to 100 ma/cm<sup>2</sup> at 150°C. The latter workers also reported that the oxidation of propane was quantitative, and measured the reaction



to be 98 ± 4% complete.

If these results can be extended to practical cells, without undue problems resulting from electrode poisoning or mechanical failures, and if a reasonable performance can be obtained from the O<sub>2</sub> (air) electrode in this electrolyte, this may represent a major break-through in fuel cell research. It should be emphasized, however, that these announcements are preliminary, and in each case involve the results of an extremely limited number of experiments. Much work remains before construction of a practical cell could be started.

Chem Engr Progress 59 No. 10 (1963)

### SECTION III - Biological Fuel Cells

The following is a condensed summary of biological fuel cells.

#### 1. Definition

Bio-electrochemistry: promotion of electrochemical processes by biological processes

Biochemical fuel cell: uses biochemical reactions to produce electrical energy from chem energy.

#### 2. Major interests

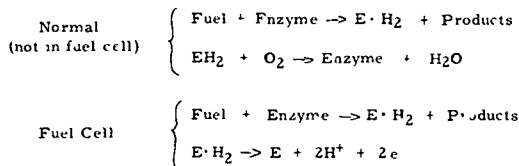
- a. Can use low grade fuels for complex reactions
- b. Can operate from natural products
- c. Can get power from industrial waste
- d. Can use to process industrial waste products  
(human & industrial, toxic, pulp & paper ind., etc)

#### 3. Limitations of biological reactions

mostly kinetic controlled, require high temp or pressure

#### 4. Catalysts

Enzymes, Microorganisms

General Process

Since micro-organisms are a group of enzymes working together as a life system, they have similar reactions.

## Role of enzyme or micro-organism

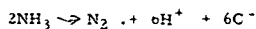
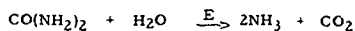
To make the electro active species available for electrode reaction (from a complex fuel).

## 5. Problems

- Must keep catalyst active (prevent denature)
- Micro organism walls slow up mass transfer.
- Usual problem of bringing together fuel, catalyst and electrode (immobilize enzyme at electrode).
- Frequently the reactions are self-poisoning.
- Frequently occur in solns of neutral pH, low ionic strength

## 6. Examples

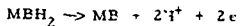
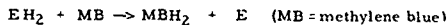
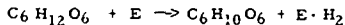
## a. Urea - Urease



Enzyme only speeds up hydrolysis (which is slow at room temp)

Still have original problems inherent in  $\text{NH}_3$  - air fuel cell

## b. Glucose - Glucose Oxidase



Merely serves as source of  $\text{H}_2$



## 7. General conclusions

- a. Limited to low current densities
- b. Still have all problems associated with corresponding direct fuel cell, with added problems caused by kinetic controlled supply of reactant.
- c. Major interest for space applications, is not for production of power, but for waste disposal, in which part of the process results in recovering of materials, and the associated small amount of power generated, merely serves to reduce the total power input required for the waste disposal.
- d. There does not seem to be any real progress toward a direct bio fuel cell in which the bio reaction and the production of electricity are combined in one step, although such should be possible.

## APPENDIX 2-NUCLEAR REACTOR

## Abstract

This section is a fairly complete analysis of the use of atomic energy for fallout shelter power sources.

## Feasibility of Using Nuclear Power Fallout Shelters

## 1. Summary

A thermoelectric-isotopic power generator seems to be the most suitable from a technical standpoint for powers up to a few hundred watts (electrical). A suitable and economical fuel in this case would probably be Strontium-90, in the form  $\text{SrTiO}_3$ .

For slightly larger powers, up to 10 kw, a thermoelectric-fission reactor power unit, using a thermal neutron, solid homogeneous fuel core, seems to be the most suitable from a technical point of view.

For higher powers, a turboelectric or thermionofission reactor system is indicated.

In any case, costs, at least in the present and foreseeable future, are very high. Unless the Government is induced to embark on a program of developing and producing cheap fuel, and to underwrite part of the cost of such devices, the cost will be prohibitive to the shelter owner. The task would be facilitated by the large development program currently undertaken in connection with the Atomic Energy Commission's SNAP program. Despite the high costs, nuclear-powered units may prove to be the most reliable, for high priority cases such as strategic government and defense installations, where reliability, rather than cost, is of prime importance.

## 2. Background

It is indicated that a power source of 1 to 10 kw(e) is needed for family--or multifamily--size fallout shelters. Such a source would very probably have to be independent of a steady source of supply of fuel that may be knocked out of action in a nuclear attack.

Nuclear energy satisfies this requirement, since a form of nuclear fuel can be chosen from among many, which would be storable and capable of generating large quantities of energy. It would have no exhaust fumes to worry about, though certain precautions as to containment and shielding must be provided.

The greater part of experience so far has been on fission-reactor power plants of tens or hundreds of megawatts electrical. Fortunately, much experience is now being gained on low power nuclear systems through the large SNAP (Systems for Nuclear Auxiliary Power) program sponsored by the A. E. C. SNAP is a multipurpose program intended to develop a wide range of compact, long-lived, light-weight nuclear power sources of different power outputs for a variety of applications. The major emphasis there, however, is on the space program. SNAP power devices are developed for such varied uses as to power instrumentation in space satellites and probes for measurement and telemetering of data (a few watts, less than 100), and for standardized satellites such as OGO (the Orbiting Geophysical Observatory) for instruments, telemetering and propulsion or station keeping (a few kilowatts).

There is presently emerging a trend toward standardization of such power devices, and in shelter applications, one should eventually be able to benefit from this trend. It is said that within 10 years, compact, off-the-shelf, high performance power supplies will be available which will approximate the ideal "black box" from which two power leads would come out.

This "ultimate" power source will become feasible because of advances in energy conversion. It will undoubtedly be nuclear since the mass of fossil fuels required will preclude such fuels.

It may be possible to induce the Government to sponsor development of such a power source for shelters. This development program would be an off-shoot of the SNAP program. The similarities in requirements are many. A power source in either case should:

- a. be reliable, trouble-free, easy to start, and preferably self-regulating.
- b. be sound structurally--it must withstand shock and vibration (in space, rocket and vehicle operation. In shelters, shock of a nearby hit, falling debris, etc.)
- c. withstand high temperature for fear of destroying the nuclear fuel package and thereby contaminating the atmosphere (in space, heat of reentry or rocket abort. In shelters, fires caused by nuclear attack.)
- d. provide heat upon demand.
- e. be sufficiently shielded (in space, for radiation belt measurements, etc. in shelters, for biological protection.)

- f. be self-regulating (in space, obvious. In shelters, because of lack of experienced personnel, or otherwise personnel under severe emotional stress).

There are many power source types investigated as auxiliary power systems, Fig. 1. It can be seen that, of those shown, and for the powers and durations envisaged, that nuclear power sources are the most feasible. There are two general kinds of nuclear devices:

- a. radioisotope systems, producing heat because of the nuclear decay process, for the watt to a few hundred watt (electrical) range, and
- b. fission reactor systems, producing heat from nuclear fission, for the kilowatt range and beyond.

### 3. Radioisotope Devices

In the space program, radioisotope devices are preferred to solar cells in many cases. Examples are the operation in the radiation belts around the earth, in opaque atmospheres, during long periods of darkness (such as the lunar night). This reasoning also obviates the use of solar cells for shelters, because of the possibility of a radioactive atmosphere, and night and cloudy operation which would necessitate a costly energy storage facility, etc.

It is generally agreed that isotopic generators are limited in application because of the general unavailability of sufficient fuel. The largest isotopic power device known is the AIS (Advanced Isotopic Source) under development. It will produce 500 w(e), will have a useful life of 1/2 yr. and will have a mass of 100 lb., exclusive of mounting, shielding and converter. The smallest fission reactor known is the SNAP-10A\*. This is a 500 w(e), 1 yr. life,  $U^{235}$ -fueled system weighing 800 lb. also without mounting, shielding or converter.

A radioisotope power unit provides a tough and continuous source of electric power, with predictable lifetime output. It can be used where frequent maintenance, refueling, recharging, etc. are difficult. Isotopic power promises eventual economic advantages (relatively) as well as reliability.

Table 1 lists the most promising radioisotope fuels and some of their characteristics.

\*Even-numbered SNAP systems utilize fission reactors, while odd-numbered ones utilize radioisotopes as an energy source.

Isotopic fuels are either fission products separated from depleted fission reactor fuels (generally  $\beta$  emitters), or special materials irradiated in fission reactors (generally  $\alpha$  emitters).

In general, the  $\beta$  emitters are cheaper. There, however, exists a shortage of facilities to separate fission products from spent reactor fuel elements. They also offer lower though still satisfactory power densities. Periods of useful operation of any fuel is relatively indicated by its half life.

The activity of a radioisotope continues to decay at an exponential rate with time whether or not electrical power is taken out of the power device it fuels. There is no way of arresting the activity of a particular radioisotope, and keeping it in a state of readiness until needed. There are, therefore, two problems connected with the use of radioisotopes as fuels for shelters.

The first stems from the fact that, since there is no assurance as to when an air attack will take place, fuel must be loaded fresh and left to decay until such a time when the energy it produces has fallen off (below that of the time of loading) sufficiently to warrant a reloading.

At the costs indicated in Table 1, it seems that a better way of power flattening would be to use a radioisotope of long half-life such as  $\text{Pu}^{238}$ ,  $\text{Cs}^{137}$  or  $\text{Sr}^{90}$ . Unfortunately long-lived isotopes also have low activities per gram and consequently low power densities.

On the basis of projected costs, however, it seems at this time that  $\text{Sr}^{90}$  may be good compromise. The low power density would not be too serious a handicap in a land-based application. Other advantages of this fuel are given under "safety" below.

Prototype units fueled with  $\text{Sr}^{90}$  are now being developed for the Coast Guard and Navy for use in Navigational and Weather stations (a buoy in Chesapeake Bay, Md., for example). These are SNAP-7A, B, C, D and E. They are 5 to 30 w(e) units. SNAP-7E produces 5 w(e) for 2 years. It contains fuel pellets of  $\text{Sr}^{90}$  in 4 cylinders in its core, in the form of Strontium Titanate. Conversion is by 60 sets of thermoelectric elements. SNAP-9 uses  $\text{Pu}^{238}$  as fuel. Its conversion system is also thermoelectric and has a design life of 5 to 10 yrs.  $\text{PuC}$  is the chemical form of fuel used for metallurgical reasons.  $\text{Cm}^{242}$  is the fuel used in SNAP-11, SNAP-13 and SLLG (Soft Lunar Landing Generator). Fueling here occurs as long as 30 days on mission.  $\text{Ce}^{144}$  is used in SNAP-1A, a 125 w(e), 200 lb. device.  $\text{Po}^{210}$  is used in SNAP-3.

The second problem is that of "dumping" the heat of reaction during inactivity. This will be discussed later.

#### Shielding Requirements

For  $\beta$  emitters, the shielding requirements are mainly due to the "Bremsstrahlung" radiations (X-rays Produced because of the deceleration of  $\beta$  particles in media) they produce.  $\alpha$  particles are considerably weaker and simpler to shield against. However ( $\alpha$ , n) reactions producing neutrons must be shielded against. In general shielding requirements are small and adequate shielding should be easily arranged within the heavy concrete structure of the shelter.

SNAP-7E is shielded by 8" cast iron (also for water pressure) and depleted Uranium. SLLG is shielded by 1.6 in. of water for safe ground handling. This reduces radiation levels to 60 mrem per hr. at 1 m (as compared with 125 without shield).

#### Containment

$\alpha$  emitters require containment of the helium gas emitted ( $\alpha$  particles are helium nuclei). Either this gas should be purged or allowed to accumulate within the fuel capsule at increasing pressures. Helium pressure for example reaches 7870 psi in 240 days of operation of SLLG, where it is retained in hollow cylindrical fuel elements, encased in a tantalum liner for chemical protection and Hastelloy C for strength. The pressure rise of course depends upon fuel quantity, void volume, and operating time. Another problem is that due to the emission of gases in chemical change (such as Oxygen from the  $\beta$  decaying  $\text{CeO}_2$ ).

#### Safety

Some fuels such as Pu and Po are poisonous and should not be inhaled or digested by living organisms. All fuels are of course radioactive. They therefore must be encased in a manner preventing accidental release to the environment. Capsules are designed in the SNAP program to survive launch pad accidents, fires, explosions and shocks.

$\text{SrTiO}_3$  used in SNAP-7E and others is biologically inert. Its melting point is high enough to resist fire. Its solubility in water is practically negligible.

#### Converter

Since only low-powered devices are feasible with isotopic fuels, and a rugged, trouble-free system is desired, the most suitable converter in this case seems to be a thermoelectric generator.

(Only a thermoelectric or a thermionic converter are feasible for powers a few hundred watts electrical).

A thermoelectric generator would convert decay heat of the radio-isotope directly to electricity with no moving parts. (A static solid-state dc-dc converter with flip-flop circuit, transformer and rectifier are used in some SNAP device to match generator output to load). Conversion efficiencies as high as 83% thermal have been achieved. Seventy percent are common. Thermoelectric efficiencies of 4.0 to 5.0%.

#### Heat Dumping

This can be done either electrically through some useful circuit such as for heating or lighting of the shelter space, or heat may be dumped at the hot junction with the help of an automatic whutter mechanism.

The thermoelectric material dictates the rate and method of dumping. Lead telluride, the most likely and only presently operational material, sublimates at hot junction temperatures greater than 1,000°F. Efficiency, on the other hand, falls off rapidly below 900°F. Thus the hot junction must be maintained between these two limits. Other promising materials under development, but which are not yet ready for use, such as Cadmium sulphide, Cobalt silicide and Gadolinium selenide, offer Seebeck coefficients comparable to lead telluride but high temperature operation as well.

SLLG (Cm<sup>242</sup>), for example, is to have power levels of 752 w(e) at encapsulation, 655 w(e) at launch and 475 w(e) at end of life. Heat is dumped by a radiator (in space) attached to the fuel capsule. The radiator is covered by a radiation insulating shutter which moves by thermal expansion of molten Sodium-potassium Alloy (NaK) in a loop near the hot junction. The shutter is fully open at the beginning of mission, and fully closed at the end.

#### Costs

The cost of the isotopic fuel is substantially greater than the cost of the rest of the system. Expected advances in conversion techniques should, however, eventually result in reduced fuel inventories and less costly systems.

The over-all cost picture, like that of all nuclear fuel, is by no means complete. Table 1, however, includes current and projected costs of some fuels. The following figures are also reported

For a 100 w(e),  $Ce^{144}$ -fueled generator with 1 year life, thermoelectric conversion (5% efficiency), and 5,000 w(th),  $6.75 \times 10^5$  curie fuel, the fuel costs are around \$70,000.

With thermionic conversion (13% efficiency expected about 1965), 2,000 w(th),  $2.7 \times 10^5$  curie fuel, the same electrical output unit would contain fuel costing "only" \$28,000.

Very little information is available on the rest of the system, i.e., converter, housing, etc. A figure of \$5,000, however, has been reported on a  $Pu^{238}$ -fueled generator. This indicates that the cost of the rest of the system contributes only little to the total cost and is therefore, not of major importance in determining the feasibility of the system.

#### 4. Reactor Units

Low-powered fission reactor systems are now being developed in the SNAP program for more advanced missions (Ranger, Surveyor, Prospector, Tiro, Transit, and for electrical propulsion). SNAP-2, a 3 kw(e) unit, is now in the process of prototype testing at design power and temperature conditions. The converter is a mercury vapor, turboelectric generator. SNAP-8 is a 30 kw(e), 600 kw(th) device, while SNAP-10A is a smaller, 500 w(e) thermoelectric conversion unit. SNAP-2 is probably the closest, power-wise, to what we are looking for in shelter operation.

SNAP reactors must start up automatically and operate unattended for long periods of time. These are characteristics which are also desirable for the shelter program. They do, however, have sophisticated and costly control systems, some of which can probably be dispensed with in shelter operation. The power cycle working fluid also need not necessarily be metallic, as it is in space operation, since cycle heat rejection temperatures are much lower on earth. This heat rejection also need not be solely by radiation as it is in space applications.

A fission reactor has the advantages of high specific power (up to  $10^6$  watt hr./lb.), compactness and ruggedness. The limitation on the amount of thermal energy generated by a fission reactor of a given type is only due to materials and heat transfer. The conversion system may be:

Thermoelectric in the range 0.1 - 10 kw

Turboelectric in the range 1 - 100 kw

Turboelectric or

) -- in the range 0.1 - 10 mw

Thermionic

)



### Reactor Type

In current thinking, fast (neutron) reactors are not under serious consideration for small-powered reactors, mainly because of their high cost (about \$1 million for one critical mass). Thermal (neutron) reactors are therefore preferred.

For thermal reactors, neutron moderation is necessary. Light and heavy water moderators have the advantage of doubling as coolants but require pressurization at operating temperatures. This results in a costly and heavy pressure vessel as well as other complications. Beryllium and graphite are suitable, though the former is costly and the latter results in a large-sized core. Zirconium hydride provides a hydrogen density, and a core size, comparable to those attained with water, and requires no pressurization. It is stable up to 1,200°F. and shows considerable promise as moderator for applications such as are being considered here.

A form of nuclear fuel that also shows promise in these applications would be fully-enriched Uranium, mixed homogeneously with the Zirconium hydride moderator resulting in a homogeneous solid-fuel type reactor. This fuel type is used in the SNAP Program, and has shown, in radiation experiments, good stability at average fluxes as high as 5 times that of SNAP-2.

### Control

Because of the small reactor size, the core neutron leakage is large and effective control is accomplished by simply varying the thickness of a reflector (which would probably be made out of Be). Variation of thickness could be affected by rotating segments of the reflector away from the core boundaries.

### Conversion

As a SNAP-10, where thermoelectric conversion is used, hot junction heat may be transferred by conduction through an annular array of thermoelectric elements. Fins may then be attached to the cold junction for heat rejection.

The fuel may be allowed to operate at temperatures higher than are possible with lead-telluride as mentioned previously. This may be circumvented, as is done in SNAP-10A, by a NaK loop between fuel and hot junctions. This also results in a reduction in mass over a simple conductive system.

In the turbogenerator method of conversion, a single shaft system may be used to reduce operational problems. The complexities,

mass and size of rotary machinery, however, are believed here to make this method less desirable than a thermoelectric one.

#### Costs

In this developmental period no costs of SNAP-size fission reactor systems are available, and probably none would be for some time. Only conjecture is possible here.

Recently published figures indicate that, for 30 mw(e) nuclear plants, projected capital costs are expected to vary, depending upon reactor type, between \$55 and 85 million, meaning \$180 to 280 per kw(e) installed.

A large power reactor usually contains many (up to 25 or more) critical masses. A low-powered reactor would require less fuel, shielding and a smaller and less costly pressure vessel, etc.

Taking these and other considerations into account, a very rough estimate would probably place the cost of mass-produced reactor systems for shelters at somewhere between 1/4 to 2 million dollars per unit.

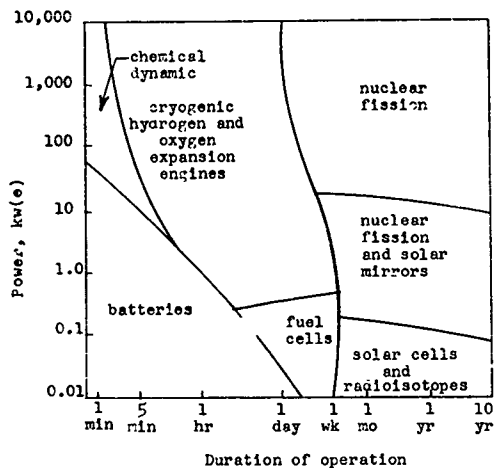


FIG. 1. AUXILIARY POWER SYSTEMS

Reference: "Nuclear Space Power Systems", NAA-SR-5650, 1960

TABLE 1.

Nuclide	Activ- ity	Half Life	Probable Form	Density g/cm <sup>3</sup>	Watt/cm <sup>3</sup>	\$/Watt Current	\$/Watt Projected
Po <sup>210</sup>	$\alpha$	138d	Po	9.3	1320	-	-
Cm <sup>242</sup>	$\alpha$	162d	Cm <sub>2</sub> O <sub>3</sub>	11.75	1159	80*	45*
Pu <sup>238</sup>	$\alpha$	86.4y	Pu	12.5	6.9		1600
Ce <sup>144</sup>	$\beta$	285d	CeO <sub>2</sub>	6.4	12.5	87	14*
Pm <sup>147</sup>	$\beta$	2.6y	Pm <sub>2</sub> O <sub>3</sub>	6.6	1.1	3000	1630*
Cs <sup>137</sup>	$\beta$	33y	CsCl	3.9	1.27	500	54*
Sr <sup>90</sup>	$\beta$	28y	SrTiO <sub>3</sub>	4.8	0.54	455	23*

\* Cost of irradiation \$100/watt extra.

+ Estimated by AEC based on construction of major separation facility.

## APPENDIX 3 - GASOLINE DECOMPOSITION AND STORAGE

## SECTION 1 Decomposition of Gasoline

On extended storage of gasoline, the most serious detrimental change in properties involves gum formation. These gums are resinous, polymeric materials of low volatility (but soluble in the gasoline) which deposit on the internal parts of an engine, primarily in the carburetor, but also in the manifold system, or the inlet valves, and even in the combustion chambers. Accumulations of these materials ultimately cause mechanical failures in the engine.

In general, the formation of gums in gasoline depends on the composition of the gasoline, and results from the oxidation of the hydrocarbons with atmospheric oxygen. The reactions are very complex, and their rates are such that most commercially available gasolines, even when treated with suitable oxidation inhibitors, cannot be stored for longer than about 12 months. The many factors involved have been discussed by Rosenwald (6), and among the important considerations (in addition to the composition of the gasoline) are the nature of the impurities present, the oxygen availability, and the temperature. The interactions of these factors can be related to the proposed mechanisms for the hydrocarbon oxidation reactions.

Effect of Gasoline Composition

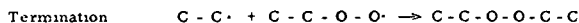
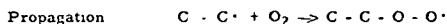
In the formation of gum by oxidation of hydrocarbons, only the unsaturated components of the gasoline (olefins) are involved. The simple olefins, containing a single carbon-carbon double bond, are not particularly harmful when present alone, but if very small amounts of reactive olefins (with conjugated double bonds) are present simultaneously, the gasoline is readily oxidized with rapid formation of gum. Although the gums generally contain higher relative proportions of nitrogen and sulfur than did the original gasoline, compounds containing these elements are not required for gum formation, and the olefins are the major source of the difficulty (6).

Although gasolines containing only saturated hydrocarbons (or aromatic hydrocarbons without oxidizable double bonds) would presumably be very stable toward air oxidation, such blends are not available. Most commercial gasolines contain about 50% saturates, 20-30% of the olefins (3). Thus the methods of improving the storage stability of commercial gasoline must involve a study of the mechanism of air oxidation of the olefins.

Olefin Oxidation

Although the detailed mechanism of olefin oxidation is highly dependent on the structure of each compound involved, it is generally believed that the process involves a sequence of steps producing a hydroperoxide through a chain reaction with free radicals. A mechanism of this sort is consistent with the physical and chemical properties of the products, since polymeric

peroxides are characteristically of low volatility, and are hard, varnish-like materials. The major steps of the reactions can be divided into three categories: an initiation step, in which a free radical is produced from the olefin; a propagation step in which the olefin radical reacts with oxygen, forming a hydroperoxide and additional radical, and a termination step, in which the chain is stopped by formation of a product not containing an additional radical. One of the many possible representations of such a process would be (6):



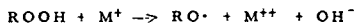
Very extensive kinetic studies of certain individual olefins have been carried out, and the rate laws indicate reactions of this general type. The relation importance of each step depends on the experimental conditions, of course, and the type of propagation or termination reaction also can be affected by parameters such as oxygen concentration and temperature. The overall rate of gum formation will depend on the individual steps.

#### Initiation Step

In order to initiate the reaction, some process must be operative in which a radical is produced. Several processes are known which are of importance in oxidation of gasoline olefins. The efficiency of the process depends on the reactivity of the olefin, and radicals are much more easily produced from olefins containing conjugated double bonds.

First, radicals can be produced by irradiation, particularly in the ultraviolet. Since the radiation must be absorbed by the molecule to be effective, the simple olefins (which do not absorb UV radiation) are much less affected than are the more complex compounds.

Second, certain heavy metals, such as copper, have a marked effect on the gum formation by accelerating the initiation step (8). This is thought to involve the decomposition of hydroperoxides to produce additional free radicals:



The extent of the effect depends on the nature of the metal, and its concentration. Usually, metals with several oxidation states are involved.

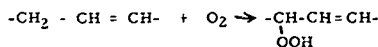
The third major initiation process results from the presence of materials which easily decompose to produce free radicals. Addition of such materials, such as benzoyl peroxide, has been used to initiate gum formation reactions in kinetic studies, but of course, would not be important in a real case. However, peroxides are produced during the gum formation reaction, and these compounds undergo thermal decomposition to produce two free radicals.



Compounds formed in reactions of this type can then abstract a hydrogen atom from hydrocarbon, thus initiating additional reaction with oxygen and eventual additional hydroperoxide formation.

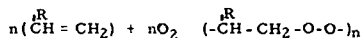
#### Propagation Step

In the presence of excess oxygen, the propagation step can involve formation of two kinds of peroxide. First, reaction with hydrogen in an active methylene group is the usual reaction of the simple olefins:



Such compounds are of low molecular weight, and as such, are volatile, however, as pointed out above, they are not stable and are involved in further reactions.

The second propagation reaction involves a direct polymerization, a normal path for olefins with conjugated double bonds:



(where R contains the second double bond of the conjugated pair)

In addition to the structural influence on the relative importance of the two propagation reactions, the direct polymerization appears to be favored at higher temperatures.

#### Termination Step

Any reaction in which no additional free radical is produced acts to terminate the chain reaction. Self-termination depends on the compounds involved, and chain lengths may range over several orders of magnitude. In all commercial gasoline, antioxidants are added to help terminate the chains and thus to improve the stability of the material. These additives usually are reducing agents (phenols, aminophenols), which terminate the chain either by reduction of the hydroperoxide, or by furnishing a hydrogen atom to a radical in the chain. The mechanism of antioxidant action is complex and depends on the nature of the compounds involved, and also on the oxygen concentration (2, 5). Many tests have been developed for evaluating the effectiveness of these additives (4, 7, 8, 9).

### Effect of Temperature

The rates of each of the three steps in the overall reaction are dependent on temperature. Qualitatively, kinetic data for many reactions can be represented by the empirical Arrhenius equation

$$k = S e^{-E_a/RT} \quad (1)$$

where  $k$  is the rate constant,  $S$  is the Arrhenius factor,  $E_a$  is the activation energy,  $R$  is the gas constant (1.987 cal. deg.  $^{-1}$  mole  $^{-1}$ ) and  $T$  is the absolute temperature. The change in the rate as a function of temperature can be derived by differentiating the logarithmic form of the Arrhenius equation to obtain

$$\frac{d(\ln k)}{dT} = \frac{E_a}{RT^2} \quad (2)$$

or by integrating Eq. 2 between limits

$$\log \frac{K_2}{K_1} = \frac{E_a}{2.303R} \left( \frac{T_2 - T_1}{T_2 T_1} \right) \quad (3)$$

For many chemical reactions, the activation energy,  $E_a$ , is in the range of 15 to 60 kcal. mole  $^{-1}$ , which is in the range of chemical bond energies. By substituting these values into equation 3, and considering temperature changes around 300°K (room temperature), it is found that for such reactions, rate constants change by a factor of two or three with a 10° change in temperature. This is the basis of the empirical rule frequently quoted that the rates of many reactions double or triple with a 10° rise in temperature in the neighborhood temperature (1).

These same concepts are generally applicable to the reactions involved in gum formation in gasoline. The initiation step is subject to wide variations in activation energy. Although it is zero for a photochemical process, values of 20 or 30 kcal. mole  $^{-1}$  are more normally involved for a peroxide decomposition initiation reaction (6). The propagation step is usually of the order of 10 kcal. mole  $^{-1}$ . These values are in the range corresponding to the normal doubling or tripling of reaction rates with 10° rise in temperature.

Such variations in rate of gum formation with temperature are actually observed, and have been used as the basis of a practical test for estimating the storage stability of gasoline (9). The gasoline samples are heated to 100°C, and the length of time required to produce a certain gum content (as measured by the standard ASTM test) is determined. These data are found to follow the empirical relation

$$\log \frac{t_1}{t_2} = B \left( \frac{T_2 - T_1}{T_2 T_1} \right) \quad (4)$$



where  $t_1$  and  $t_2$  are the times required to produce a specified amount of gum at the temperatures  $T_1$  and  $T_2$ . Since  $t_1$  and  $t_2$  are inverse functions of the rate of gum formation, the comparison with Eq. 3 is obvious. Thus it has been demonstrated experimentally that the reactions involved in gum formation in gasoline by olefin oxidation are of the type which follow the Arrhenius equation. The constant  $B$  has been measured in the range of 5000 to 6000, corresponding to activation energies of the order of 25 kcal. mole<sup>-1</sup>, and corresponding to time ratios of 1000 to 5000. (The time ratio is defined as the number of hours at 30°C required to form the same amount of gum as would be produced in one hour at 100°C). The fact that accelerated gum formation tests of this sort, carried out at 100°C, can be extrapolated reasonably well to predict storage stability at room temperature indicates that the activation energy is not a function of temperature.

If an inhibitor has been added to the gasoline, the effect of temperature is slightly different, in that an induction period is observed, during which gum formation is slowed markedly by the inhibitor. However, as soon as the inhibitor has been used up, the normal increase in gum formation takes place as described above. In general, the activation energy for the inhibiting reaction is lower than that of the oxidation reaction, and thus the induction period also is increased at lower temperatures (2).

#### Effect of Oxygen Concentration

Since oxygen is consumed in the processes related to gum formation, the partial pressure of oxygen also has an effect on the overall rate of the reactions. At constant temperature, the data can be described by the empirical relation

$$\log \frac{t_1}{t_2} = D \log \frac{P_1}{P_2} \quad (5)$$

where  $t_1$  and  $t_2$ , as before, are the times required to produce specified amounts of gum in gasoline exposed to oxygen under pressures  $P_1$  and  $P_2$ . The constant  $D$  is called the oxygen pressure coefficient, and values have been measured in the range of -0.08 to -0.5, which correspond to time ratios ranging from 1.5 to 7. (The time ratio is defined as the number of hours under normal atmospheric conditions required to form the same amount of gum as would be formed in 1 hour under 100 pounds per square inch pure oxygen). Thus the effects of oxygen pressure (at these concentration levels) are not quite as marked as the temperature effect, nevertheless, significant changes in rate of gum formation are observed, and if the oxygen content in the closed sample is depleted, further gum formation does not take place.

### Extending Storage Stability of Gasoline

Probably the most straightforward approach to storing gasoline for long periods of time would be to use a stable blend. Although all commercial blends contain large amounts of olefins, "straight-run" or "virgin naphtha" blends are essentially completely free of oxidizable compounds. Some experimental gasolines also contain only saturated and aromatic hydrocarbons, and presumably would be stable for extended periods. For special purposes, it might be possible to obtain reasonable quantities of such gasolines.

However, these blends would never be generally available, and therefore, storage of typical commercial gasolines becomes the major problem. One approach would involve chemical treatment of the material before storage. The most obvious treatment would be to remove the olefins, but this is not practical, since it would be a relatively complex and wasteful process. Therefore, the oxidation cannot be eliminated but the stability might be extended slightly by chemical decomposition of any hydroperoxides present on receipt of the sample, removal of metal ions, etc. Unfortunately, one cannot add oxidation inhibitors without limit, as other effects on the properties of the fuel become important, and in all properly prepared blends, inhibitors have been added at the refinery to the maximum practical limit. Thus, in general, extensive chemical treatment of the gasoline is not practical, and in addition, only minor improvement in stability would be expected.

Probably the most promising approach to increasing storage stability of gasoline involves the physical handling procedures. First, it is probably that significant improvement in storage stability would be observed if the storage temperature were to be reduced. The empirical rule of relating rate of reaction and temperature would almost certainly be applicable to both the initiation and propagation steps. Thus, one would expect to observe the rate of gum formation reduced to one-half or one-third for each 10°C reduction in temperature. Furthermore, lowering the temperature would have an effect on the action of any inhibitor present, and would extend the induction period by a significant amount.

A second important factor in increasing the storage stability of gasoline would be to reduce all extraneous sources of radiation. Although the initiation steps are normally considered to involve UV radiation, X-rays and stray radioactivity could also produce chain starting radicals. For Civil Defense applications, proper location of the storage tanks could have a marked effect on the gum formation.

A third factor involves the presence of metals which can initiate chain reactions by reacting with hydroperoxides to produce additional radicals. Even if the major portions of such contaminants are removed, metals can be re-introduced on storage in metal containers. Thus, the use of glass or glass-lined tanks for storage would be an important factor in improving stability.

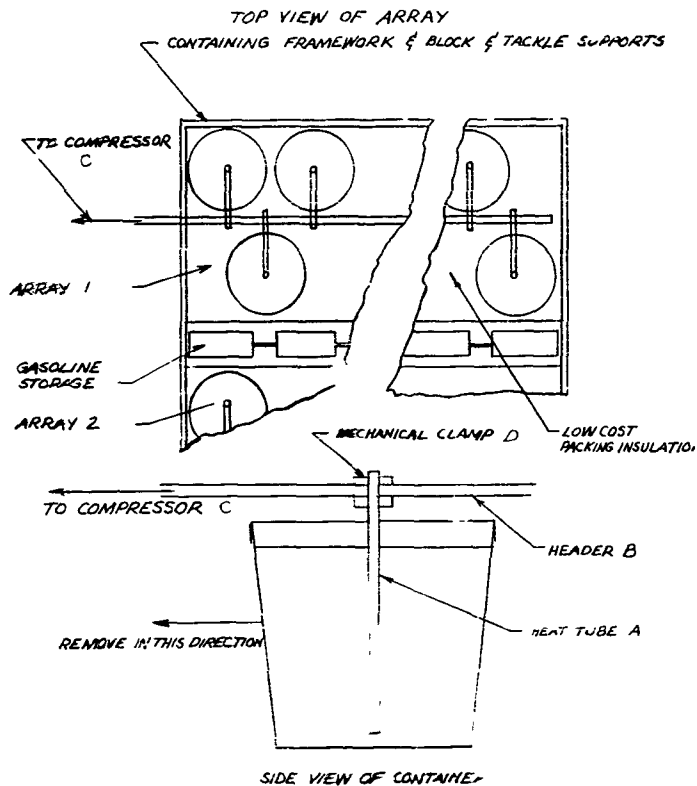
The fourth point involves the availability of oxygen. Even if no particular effort were made to remove oxygen before storage, gum formation could be limited markedly by storing the gasoline in a closed system. Once the oxygen initially present was depleted, gum formation would stop, and the gasoline would presumably be stable thereafter on extended storage.

Thus, improving the storage stability of gasoline appears feasible. The effect of the two most important factors (temperature and oxygen content) could be determined readily for any particular gasoline sample by using the accelerated storage stability tests already described (9), and there is good evidence that these data can be extrapolated to low temperatures and low oxygen pressures.

In conclusion, it appears that merely by using care in physical arrangement of storage facilities, a marked increase in the storage stability of gasoline could be obtained and that the problems associated with the storage of large quantities of gasoline are not insurmountable when smaller quantities of gasoline are involved.

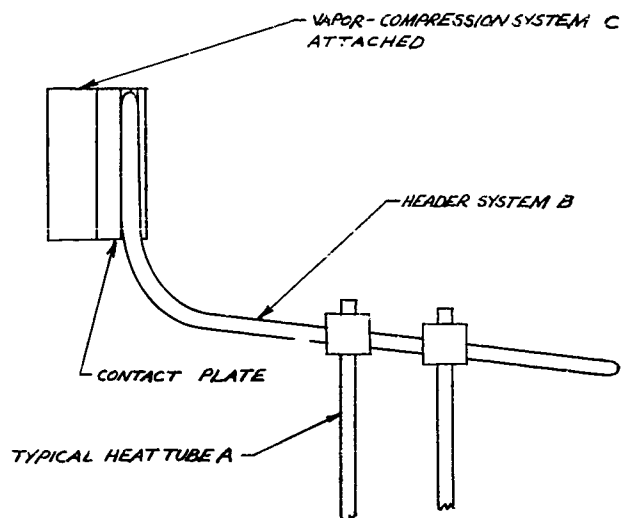
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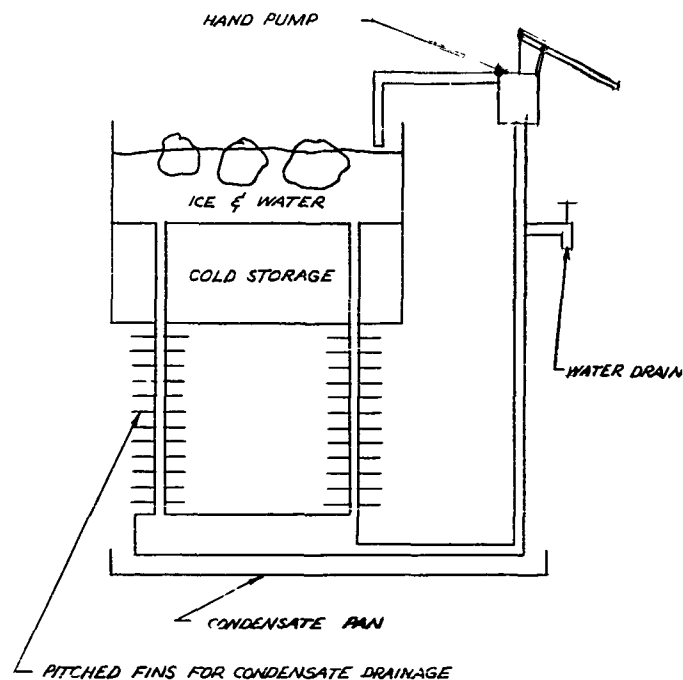
SKETCH OF ICE STORAGE ARRANGEMENT

FIG 7-



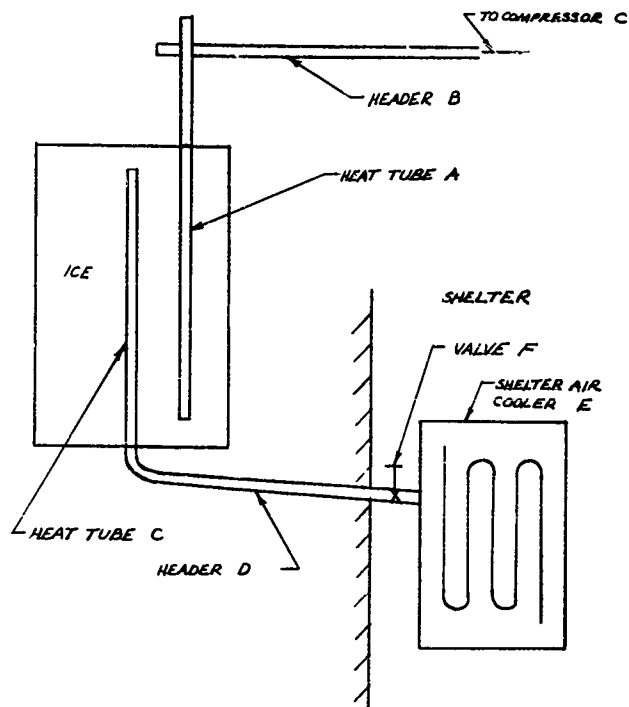
SCHEMATIC OF REFRIGERATION SYSTEM

FIG 76



PORTABLE ICE-COOLING SYSTEM

FIG. 8a



NON-PORTABLE ICE-COOLING SYSTEM

FIG. 86

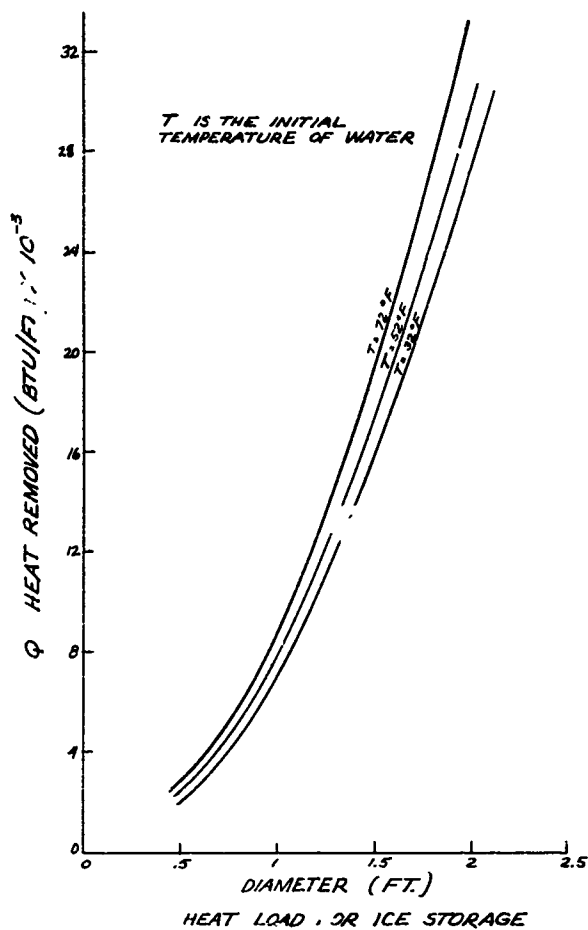


FIG. 9



## APPENDIX 3 - GASOLINE DECOMPOSITION AND STORAGE

## SECTION II Cold Storage of Gasoline

## Ice Storage

Water is a low cost refrigerant. If a quantity of water was placed in a container located in the shelter area and then frozen via refrigeration, it could serve as the heat sink for air conditioning. The freezing operation could be accomplished shortly after the unit installation and the ice mass could be kept frozen by a small compressor system that could operate either continuously or intermittently (on low cost central-station power) until the blast caused power failure. The ice would be available at this time for consumption over the emergency period.

The advantages of such a unit are:

- a. Perishable materials such as the fuel supply for electric power generation equipment could be stored in the cold area. Using the general chemical formula that chemical reaction rates decrease by a factor of 2 for every 18°F. decrease in temperature, these materials (such as fuels and possibly medical supplies, vitamins, etc.) would be kept as low as 0°F. The decomposition rate would be less by a factor of 16 times ( $2^4$ ) for 0°F. storage as contrasted to 72°F. storage.
- b. The cooling is independent of an ambient heat sink. Cooling could be achieved even though the entire shelter area is near a fire storm.
- c. There would be no power requirement after power failure for a heat pumping process.
- d. There would be no external heat sink that could be damaged by the blast.
- e. The melted ice (liquid water) would be available for utilization in the shelter.
- f. Both the refrigerant and equipment would have stability for long storage. However, in event of an accident, the melting of the ice would be easily detected and warn of improper equipment functioning. In fact, by proper circuitry, the warning signal could be sent to the local Civil Defense Headquarters.

Figure 7a is a 10 x 10 array consisting of 100 -20 - gallon garbage cans filled with water. In the center of each can a heat-pump tube (A) is located, which allows removal of heat by means of a vapor-compressor refrigeration system (C) through a distribution system (B). This system could easily freeze the water in the 100-garbage cans to ice in less than 100 days.

The heat tubes (a) and distribution tube (B) and the compressor system (C) are physically separated units so that a local failure will not render the entire system inoperable. The functioning of the various components of the system can be observed by feeling the heat tube or detecting the presence of liquid water once the stored water is completely frozen.

The construction of the system will be such that two adjacent rows will be connected to the same distribution header.

This is shown in Figure 7a. Gasoline may be stored between rows not connected by a common header. Device D is a clamping arrangement to transfer heat from the two heat tubes to the common header by conduction. This allows removal of cans of ice for use in the shelter as required (possibly by means of a block and tackle). Figure 7b also shows the attachment of the compressor (C) to the distribution tube (B) so that heat is exchanged by conduction.

A portable air cooler (and ice box) is shown in Figure 8a. Water is circulated over the ice in the ice chest and then through finned tubes to cool air passing over the tubes. The excess water is drained off for consumption in the shelter when the unit is recharged with ice.

Figure 8b shows a method by which movement of the ice cans is eliminated. The heat tube (A), header (B), and compressor (C) are identical to those in Figure 7a. However, an additional heat tube (C) and header (D) are added along with valve (F) and air cooler in the shelter (E).

In the storage period, valve (F) is closed such that the heat transferred into the ice tank is rather small (essentially by conduction through any vapor in header (D) and the piping). Thus the freezing process will occur essentially as shown in Figure 7a.

When the emergency occurs, the compressor (C) will most likely cease to function and header (B) will increase in temperature. However, heat tube A will allow very little heat to be transferred into the ice block because of the one way nature of heat tube (A), sometimes called a "thermal diode."

Valve (F) is then opened and the header (D) becomes active in transferring heat from the shelter (via air cooler (E)) into the ice block heat sink. Adjustment of valve (F) would regulate the rate of cooling. Thus, the shelter may be cooled without reliance on rejection of heat from a compressor system in the environment. Of course, the vapor-compression refrigeration system may continue to operate on shelter auxiliary power if desirable and thus effectively increase the capacity of the ice heat sink.

#### Analysis of Ice Storage Method

An analysis was made to determine the freezing rate of ice forming on a refrigeration tube. The solution available in the literature does not satisfy boundary conditions that may be expected in freezing water into ice in a well insulated

container. However, it was found that a cylinder of ice having a two foot diameter and one foot height may be frozen from 32°F. water in 21.7 days and 10.9 days with heat removal rates of 50 and 100 BTU/Hr. respectively.

Figure 9 shows the total heat (BTU per foot of length) that must be removed in order to freeze water from some particular initial temperature as a function of the diameter of the container. Thus, for example, a two foot diameter by two foot high container with water initially at 72°F. would require removal of 66,000 BTU. During an emergency, this heat sink would then provide total heat removal for an active person for approximately 100 hours. This may be increased even more if provision is made for passing unsaturated ambient air over the container. The mass transfer to the air would result in some cooling of the water and substantial cooling of the air prior to entering the shelter.

APPENDIX 4  
ANALYSIS OF VAPOR-EXPANSION  
TURBINES AND ENGINES

INTRODUCTION

This section contains a technically-complete cycle analysis and parameter study of reaction and impulse turbines. Analysis of reciprocating engines will be included in the final report.

The thermodynamical equations have been developed for an impulse and a reaction turbine; water and Freon 113 have been examined as potential working fluids in a hermetically sealed engine. The cycle analysis will be made more detailed in the final report.

Water was inspected because of the need to determine a reference standard for evaluating potential working fluids in a small-horsepower prime mover. Freon 113 was selected (after performing a screening process) as a thermodynamically promising fluid for these devices. This prediction is confirmed in that a power cycle utilizing Freon 113 had an overall thermal efficiency of approximately 16 per cent (exclusive of boiler efficiency) whereas water had an over-all thermal efficiency of approximately 6 per cent.

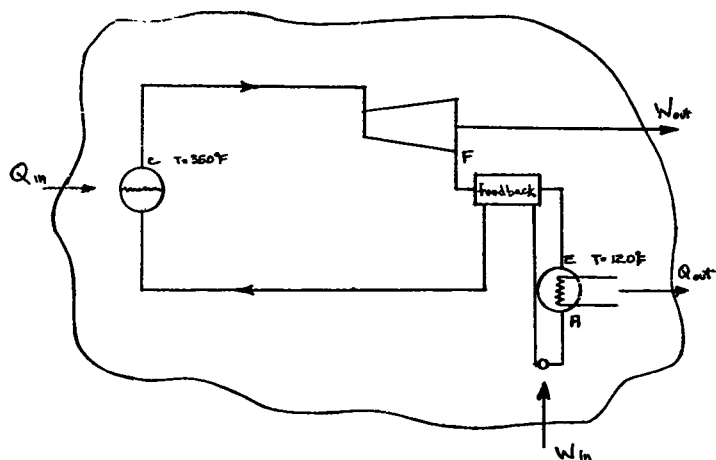
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Turbine Plant -- with Feedback

## SECTION I Impulse Turbine

Introduction

The power output of a turbine is a function of the force acting on the blades and the mean blade velocity (F. U.). Due to the tensile stresses set up in the disc holding the blades, mean blade speeds are commonly limited to about 700 f. p. s. on discs of up to about 3 ft. diameter. It can be shown (13-) that for a single velocity-stage impulse turbine the conditions for best operating efficiency result when the ratio of blade velocity to vapour jet velocity ( $\lambda$ ) is close to 0.47. (This is not true for a two velocity-stage turbine. The ratio then can be shown to be 0.26). Maximum vapour jet velocity in a single stage turbine is, therefore, kept to approximately 1,400 f. p. s. This amounts to a kinetic energy per lb.<sub>m</sub> of vapour ( $\frac{v^2}{2g_c}$ ) of 30,400 ft.-lb.<sub>f</sub>/lb.<sub>m</sub> which represents a maximum utilizable

enthalpy drop across the nozzles of approximately 40 BTU/lb.<sub>m</sub>.

A vapour having an available energy of up to 40 BTU/lb.<sub>m</sub> for the range of operating temperatures in use would, therefore, be suited to a small turbine running on one row of blades. For example a unit having a brake engine efficiency of 70% and a vapour feed rate of 1 lb.<sub>m</sub>/sec. will produce,  $0.70 \times 1 \times 40 \times 778/55 = 39.6$  HP when the ideal (isentropic) available energy (enthalpy drop) across the nozzles is 40 BTU/lb.<sub>m</sub>. It will be noted that a combination of brake engine eff., flow rate and available energy determine the output, with most room for variation occurring in the last two. A good overall thermal efficiency requires in addition that the output be achieved with a minimum of net energy input.

The operating conditions on which calculations are based in this report are saturated vapour at 350°F. and a condenser temperature of 120°F. The working fluid being used is Freon 113. Properties of this fluid up to 210°F. may be found in Reference (2). For conditions beyond this temperature data may be extrapolated by the Cox method or can be obtained from the manufacturer. The maximum available energy for Freon 113 operating between the above temperatures is, according to manufacturer's data, approximately 20.5 BTU/lb.<sub>m</sub>. By comparison, the available energy for steam is 216 BTU/lb.<sub>m</sub>, which cannot be used efficiently by a small turbine of the type under consideration. The alternative is to go into velocity--and possibly pressure-compounding with a consequent increase in expense.

A small turbine, therefore, necessitates use of fluid other than steam. Freon 113 is an example of such a fluid; with its high molecular weight and low heat content per lb.<sub>m</sub>, it is shown to perform more effectively than steam.

Breakdown of EfficienciesA. Cycle Efficiencies

- i Ideal overall thermal efficiency (Neglecting boiler efficiency and pumpwork)

$$\eta_K = \frac{\Delta h_{(isentropic)}}{Q_{(added)}}$$

- ii Actual internal thermal efficiency

$$\eta_{K1} = \frac{\Delta h_{(actual)}}{Q_{(added)}} \quad \text{Where } \Delta h_{(actual)} = \Delta h_{(isent.)} - \sum \text{losses (a)*}$$

- iii Actual overall (brake) thermal efficiency

$$\eta_{Kb} = \frac{\Delta h_{(actual)}}{Q_{(added)}} - \frac{\sum \text{losses (b)**}}{Q_{(added)}}$$

B. Process Efficiencies

- i Internal engine efficiency (stage efficiency in single stage turbine):

$$\eta_e = \frac{\Delta h_{(actual)}}{\Delta h_{(isent.)}}$$

- ii Brake engine efficiency

$$\eta_b = \frac{\Delta h_{(actual)} - \sum \text{losses (b)}}{\Delta h_{(isent.)}}$$

\*Losses (a): Nozzle friction  
Blading losses (other than windage)  
Disc friction  
Blade windage  
Gland leakage  
Radiation losses

\*\*Losses (b): Bearing friction  
Reduction gear friction  
Governor drive work  
Feed-pump work



## C. Other Performance Criteria

$$1 \quad \text{Heat rate} = \frac{\text{heat transferred per unit time}}{\text{work output}}$$

$$11 \quad \text{Work ratio} = \frac{\text{net work from cycle}}{\text{total work from cycle}}$$

$$111 \quad \text{Vapour rate} = \text{lb}_m \text{ vapour per unit time per HP output} =$$

$$\frac{2545}{\eta_b \Delta h \text{ (isent.)}} \quad \frac{\text{lb}_m}{\text{hr. -HP}}$$

Note: The vapour rate together with the exhaust conditions are instrumental in determining the physical size of the turbine. ( $\dot{Q}$ )

Determination of Losses

Nozzle Friction--Loss of available energy occurs in the nozzle due to fluid friction. K. E. Becomes converted into heat causing a reduction in velocity and increase in entropy. Consequently letting

$$\eta_n = \frac{V_1 \text{ (actual)}}{V_1 \text{ (ideal)}}$$

the nozzle efficiency is

$$\eta_n = \frac{\Delta h \text{ actual in nozzle}}{\Delta h \text{ isent. in nozzle}}$$

Most investigations into values of  $\eta_n$  have been confined to steam (1, 4) and few agree exactly with each other. Indications are that  $\eta_n = f(R_e, \text{roughness, nozzle shape, length, curvature and angle, exit and entrance conditions, and fluid velocity})$ . Approximate calculation of the friction loss can be accomplished by dividing the nozzle into sections along its length and applying the Darcy formula,

$$h_m = \frac{f}{D_e} \frac{L V^2}{2 g_c}$$

to each section. This ignores secondary effects of curvature, shape, entrance and exit, etc.

In general, for the high Re encountered in nozzles, friction losses are proportional to  $V^2$ . Use of the  $K_n$  data for steam would therefore be permissible.

#### Blading Losses

The efficiency of conversion of kinetic energy into mechanical energy by the nozzle and wheel arrangement is expressed by

$$\eta_B = \frac{\text{Blade Work}}{KE (\text{Vapour jet})}$$

This expression includes all effects of blade and nozzle angles, velocity ratio  $\lambda$ , and covers blade friction and leaving velocity losses. For a single wheel turbine it can be shown that

$$\eta_B = Q (1 + k_b c) (\rho \cos \alpha - \rho^2)$$

#### Effect of Velocity Ratio

On differentiating the express.. 'or  $\eta_B$  with respect to  $\lambda$  and setting to zero in order to find a maximum, there results

$$\lambda = \cos \alpha / 2$$

The best velocity ratio is, therefore a function of the nozzle angle, with the highest and most efficient occurring at small angles. For practical reasons nozzle angles are usually kept between  $15^\circ - 30^\circ$ .

#### Blade Friction

Overall friction losses in the blades are expressed in the form of a coefficient  $k_b$

$$k_b = \frac{u_1}{u_2}$$

The coefficient  $k_b$  is a function of,

- Blade width and height
- Blade angles
- Edge thickness of blades
- Curvature of blades
- Thickness of nozzle partition at exit
- Fluid velocity

Values of  $k_b$  plotted against velocity, blade width and curvature may be found in ref. 4 and used as a reasonable guide.

### Note on Design of Blades

It is usually recommended that blade heights be kept within 2 and 20 per cent of the diameter with a minimum height of 3/8". Experiments on nozzle and blade heights below 0.75" show excessive drops in stage efficiency (4). The alternative is to have partial admission of vapour around the periphery, which introduces blade windage losses (see later section).

Blade pitch (distance between corresponding points on successive blades) also influences efficiency. Most efficient pitch is given by

$$\rho_b = \frac{R}{2\pi \sin \beta_1}$$

where R = radius of curvature of blade.

### Disc Friction

The turbine wheel rotates in an atmosphere of vapour at condenser pressure. Work is expended in overcoming the frictional resistance as the wheel rotates. Resistance is usually expressed as a drag coefficient.

$$C_D = \frac{\text{Drag force}}{1/2 \rho v^2 A} = \frac{D}{1/2 \rho v^2 A}$$

For the case of rotating disc, the drag torque on both sides becomes

$$C_m = \frac{2 DR}{1/2 \rho v^2 R^3} = \frac{2 M}{1/2 \rho \omega^2 R^5}$$

where  $\rho$  here indicates mass density ( $\text{lb./ft.}^3$ )

Schlichting (5) has plotted experimental and theoretical values of  $C_m$  for well-encased discs-- as found in turbines. The horsepower loss then becomes

$$\text{HP}_d = \frac{(M \omega)^2 \rho}{550} = \frac{C_m 1/2 \omega^2 R^5 \omega}{g_c \times 550}$$

Kearton (1) has derived an empirical formula from experiments by Brown Boveri, Inc., on various gases for well encased discs.

$$\text{HP}_d = C D^2 \left( \frac{U}{100} \right)^3 \rho$$

$$\text{Where } \log_{10} C = .90 - 0.2 \log_{10} \left( \frac{D U \rho}{\omega} \right)$$

D = Disc diameter

U = Peripheral velocity of disc  $\text{ft./sec}$

$\rho$  = Mass density of fluid  $\text{lb./ft.}^3$

### Blade Windage

Where there is partial admission the turbine blades churn up vapours as they pass through the non-active zones, thereby reducing the final output of work. Formulas for the loss in power appear in reference (4) and (9) and show it to be proportional to

$$u^3 D h \phi(\Theta)$$

Where  $h$  = blade height

$(\Theta)$  = per cent active circumference

Calculations from these formulas indicate that this loss may be up to five times the disc friction. However, if precautions are taken to shield the blading in the non-active zones, considerable reductions can be obtained and the formulas given may be reduced by a factor of 0.25-0.50 (9). The authors in reference (6) assume blade windage losses to be of the same order as disc friction.

### Residual Velocity

The absolute velocity with which the vapour leaves the final blades is a part of the blading losses. It can be calculated by

$$E_{\text{loss}} = \frac{V_2^2}{2g_c J}$$

For a single-row turbine this loss is usually higher than in velocity-staged turbines but can be modified by the blade exit angle.

### Gland Leakage

Some vapour can be expected to escape out of the turbine at the high pressure end, and some air may leak into the unit at the low pressure end--depending on exit pressure. In compounded turbines additional leakages occur around blade tips and nozzle diaphragms. A labyrinth type gland is usually used to minimize leakage out, and a hydraulic gland to prevent leakage in. Normally leakage represents no more than 1% output loss.

### Radiation Losses

For a small turbine operating at comparatively low temperatures these losses will be minimal.

### Bearing Losses

Journal bearings are usually employed for smaller turbines. The design and power consumption of such bearings is described in detail in ref. 7. The main factors influencing power loss are.

Load on bearing  
 Speed of rotation  
 Length and diameter of bearing  
 Contact angle between shaft and journal  
 Journal clearance  
 Oil viscosity

Rough calculations for a 1 ft. diameter steel disc exerting a load of 25 lbs. and rotating at 8,000 rpm in a  $\frac{1}{4}$ " x 1" journal indicate a consumption of between 0.2 to 0.15 hp depending on design parameters. As assumption of 2% output loss in the bearings would, therefore, appear to be a liberal allowance.

#### Turbine Design

For a detailed account see refs (1) and (4). But for a good, briefer treatment see ref. (9).

#### SAMPLE CALCULATION

##### Operating Conditions

Turbine inlet  $T_C = 350^\circ\text{F}$ .  $P_C = 283.3$  psia (sat. vap.)

Condenser  $T_E = 120^\circ\text{F}$ .  $P_E = 15.4$  psia (sat. vap.)

(Subscripts as in Figs. 1 and 2)

Disc diameter 1 ft. Desired output = 15 hp Full admission.

Fluid Properties (According to manufacturer's data and ref. 2.)

$h_C = 124.8$  B/lb.<sub>m</sub>  $\rho_C = 9.489$  lb.<sub>m</sub>/ft.<sup>3</sup>  $S_e = 0.1905$  B/lb.<sub>m</sub> °F.

$h_D = 105.0$  B/lb.<sub>m</sub>  $P_D = \frac{1}{2.4}$  lb.<sub>m</sub>/ft.<sup>3</sup>  $S_D = 0.1905$  B/lb.<sub>m</sub> °F.

$h_E = 96.41$  B/lb.<sub>m</sub>  $P_E = \frac{1}{2.078}$  lb.<sub>m</sub>/ft.<sup>3</sup>  $S_E = 0.1758$  B/lb.<sub>m</sub> °F.

$h_A = 33.48$  B/lb.<sub>m</sub>  $P_A = 94$  lb.<sub>m</sub>/ft.<sup>3</sup>  $S_A = 0.0673$  B/lb.<sub>m</sub> °F.

##### Ideal Available Energy

$$\Delta h_{(\text{isentropic})} = h_C - h_D = 124.8 - 105.00 = \underline{19.8 \text{ BTU/lb}}$$

Where  $h_D$  is extrapolated from P-h chart in ref. 2.

Nozzle LossTheoretical (Ideal) Velocity

$$\frac{V_{\text{inlet}}^2 - V_{\text{outlet (ideal)}}^2}{2 g_c} = \frac{778}{778} \Delta h_{\text{(isentropic)}}$$

$$\text{Assume } V_{\text{inlet}} \approx 0$$

Then

$$V_{\text{outlet (ideal)}} = 223.8 \sqrt{19.8} = \underline{997 \text{ fps}}$$

With this theoretical velocity and data of refs. 1 &amp; 4 assume

$$k_n = 0.95$$

$$k_n^2 = 0.903$$

Then

$$V_{\text{outlet (actual)}} = 223.8 \sqrt{0.903 \times 19.8} = \underline{947 \text{ fps}}$$

$$\text{Nozzle Loss} = 19.8 \times 0.097 = \underline{1.92 \text{ BTU/lb.}_m}$$

Blade Losses

$$\text{Let nozzle angle } \alpha_1 = 20^\circ$$

$$f = \frac{\cos \alpha_1}{2} = \frac{0.942}{2} = 0.471$$

$$U = 0.471 \times 947 = \underline{445 \text{ fps}} = \text{mean blade speed}$$

From data of refs. 1 and 4 assume

$$k_b = 0.85$$

Velocity Diagram Scale 1" = 200 fps

$$U = 2.23'$$

$$V_1 = 4.73''$$

$$U_1 = 2.75'' = 550 \text{ fps}$$

(from diagram)

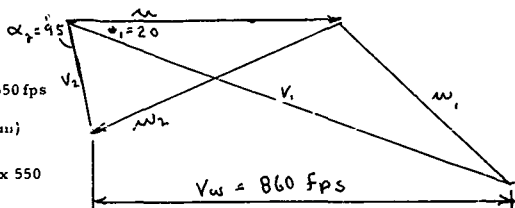
$$U_2 = 0.85 \times 550$$

$$= 467 \text{ fps}$$

$$= 2.34''$$

$$V_2 = 1'' = 200 \text{ fps}$$

$$V_w = \text{Velocity of whirl. Blade output in HP} = \frac{m}{g_c} \frac{V_w}{x 550}$$



For calculation of proper  $B_2$  the following formula applies to satisfy continuity requirements.

$$S_n B_2 = \frac{1}{P_m} \left( \frac{144}{f_2} \times \frac{w}{f_2} \times \frac{V_2}{U_2} + \pi \right) \quad (\text{See ref. 1 p. 191})$$

for which design data of the wheel is required. An assumption of  $B_2 = 25^\circ$  has been made as being representative and giving almost maximum impulse ( $V_2$  leaves at almost  $90^\circ$  to wheel).

Design Note Major reductions in exit angle may have to be compensated by increase in blade height at exit in order to satisfy the continuity equation

Then

$$\eta_B = 2 \times 0.47(0.942 - 0.47) (1 + 0.85 \frac{\cos 25^\circ}{\cos 365^\circ})$$

$$\text{Blade Loss} = (19.80 - 1.92) 0.133$$

$$= \underline{2.38 \text{ B/lb. m}}$$

Disc Friction

Method 1 -- ref. 5

$$HP_d = \frac{C_m \frac{1}{2} P^2 R^5}{550 g_c} = \frac{C_m P U^3 \times R^2}{\times 550 \times g_c}$$

$$R = 0.5$$

$$U = 445 \text{ fps}$$

$$= 0.416 \frac{\text{lb. m}}{\text{ft.}^2} \quad (\text{isentropic case}) - \text{actual } P \text{ will be reduced due to reheat, and friction loss is lowered}$$

$$\mu = 0.726 \times 10^{-5} \frac{\text{lb. m}}{\text{ft. sec}} \quad \text{ref. 2, p. 94}$$

$$R_e = \frac{0.5 \times 445 \times 0.416}{0.726 \times 10^{-5}} = 1.271 \times 10^7$$

$$\text{From Fig. 21-8 ref. 5 } C_m = 0.0032$$

$$\circ \circ \circ \quad HP_d = \frac{0.0032}{2} \times \frac{0.416 \times 445^3 \times 0.5^2}{550 \times 32.2} = \underline{0.818 \text{ HP}}$$

Method 2 -- ref. 1

$$HP_d = CD^2 \left( \frac{U}{100} \right)^3 \rho$$

$$\log_{10} C = \overline{1.90} - 0.20 \log_{10} \left( \frac{DUP}{\mu} \right) \frac{DUP}{\mu} = 2.542 \times 10^7$$

$$= \overline{1.90} - 1.478$$

$$= \overline{2.422}$$

$$\circ \circ \circ \quad C = 0.0264$$

$$HP_d = 0.0264 \times 1^2 \times 4.43^3 \quad 0.416$$

$$= \underline{0.955 \text{ HP}}$$

Continued



Then assume disc friction loss is 1 HP

$$\text{For } 1 \text{ lb}_m / \text{sec. flow} \quad \text{Loss} = \frac{1 \times 550}{1 \times 778} = \underline{0.707 \text{ BTU/lb.}_m}$$

#### Bearing Loss

Assume 2% of output

#### Reduction Gearing and Governor Drive

Assume 3% of output

Then total loss in bearings, reduction gear, and governor, = 5%

#### Pump Work

$$\text{Pump Work} = \frac{v_f \Delta P \times 144}{778 \times \eta_p} = \frac{0.01063 (250-15.4) \times 144}{778 \times 0.4}$$

$$v_f = 0.01063 \frac{f \lambda^3}{\omega_m} = \underline{1.3 \text{ BTU/lb.}_m}$$

$$\Delta P = 250-15.4 \text{ psi}$$

$$\eta_p = 0.4 \text{ (small pump efficiency)}$$

#### Process Efficiencies

Overall engine eff. ( $\eta_e$ )

$$\eta_e = \frac{\Delta h_{\text{(isentropic)}} - \sum \text{losses (a)}}{\Delta h_{\text{(isent.)}}}$$

$\sum \text{losses (a)}$

Nozzle	=	1.92 B/lb. <sub>m</sub>	
Blade	=	2.38 "	
Disc	=	0.707	(assuming approx. 1 lb. <sub>m</sub> /sec. flow)
Total	=	5.007	(neglecting leakage and radiation)

$$\eta_e = \frac{19.8 - 5.01}{19.8} = \underline{0.747}$$

Brake engine eff. ( $\eta_b$ )

$$\begin{aligned}\text{Available energy at output shaft} &= 19.8 \times 0.747 \times 0.95 \\ &= 14.08 \text{ BTU/lb.}_m\end{aligned}$$

$$\text{Pump Work} = 1.3 \text{ BTU/lb.}_m$$

Then available energy to generator shaft

$$\begin{aligned}&= 14.08 - 1.30 \\ &= 12.78 \text{ BTU/lb.}_m\end{aligned}$$

and

$$\eta_b = \frac{12.78}{19.8} = \underline{0.645}$$

Then actual vapour flow required for 15 HP output

$$\frac{15 \times 545}{0.645 \times 19.8} \quad \underline{3600 \text{ lb.}_m} = \underline{0.834 \frac{\text{lb.}_m}{\text{sec.}}}$$

$$\text{and actual disc loss is } \frac{0.707}{0.834} = 0.847 \text{ B /lb.}_m$$

Actual Overall Thermal Efficiency ( $\eta_{ro}$ )

$$\begin{aligned}Q_{\text{added}} &= h_c - h = 124.8 - 33.48 \\ \text{(without feedback)} &= 91.32 \text{ BTU/lb.}_m\end{aligned}$$

$$\begin{aligned}Q_{\text{added}} &= h_c - h - h_{\text{feedback}} \\ \text{(with feedback)} &\end{aligned}$$

$$h_{\text{feedback}} = h_i - h_E$$

$$h = h_D + \text{losses (a)} = 105.9 + 5.01 = 110.1 \text{ BTU/lb.}_m$$

Continued

$$h_{feedback} = 110.01 - 96.41 = 13.60 \text{ BTU/lb.}_m$$

let heat exchanger effectiveness = 0.8

$$h_{feedback \text{ actual}} = 0.8 \times 13.60 = 10.87 \text{ B/lb.}_m$$

$$\text{and } Q_{\text{(added with feedback)}} = 91.32 - 10.87 = \underline{80.45 \text{ BTU/lb.}_m}$$

This neglects work supplied by pump

Then

$$\eta_{ro} = \frac{\text{Net Work Output}}{Q_{\text{added (with feedback)}}}$$

$$= \frac{12.78}{80.45} = \underline{0.159}$$

If boiler efficiency is 0.9

$$\eta_{ro} = 0.159 \times 0.9 = \underline{0.143}$$

#### Partial Admission -

Assume blade windage loss = HP (cf disc loss of 1 HP)  
(Check using formulas of ref. 9).

then loss = 1.414 B/lb. <sub>m</sub> (at 1 lb. <sub>m</sub>/sec. flow, and

$$\eta_{ro} = \frac{12.78 - 1.414}{80.45} = 0.141$$

Fig 1 T-S Diagram for F-113

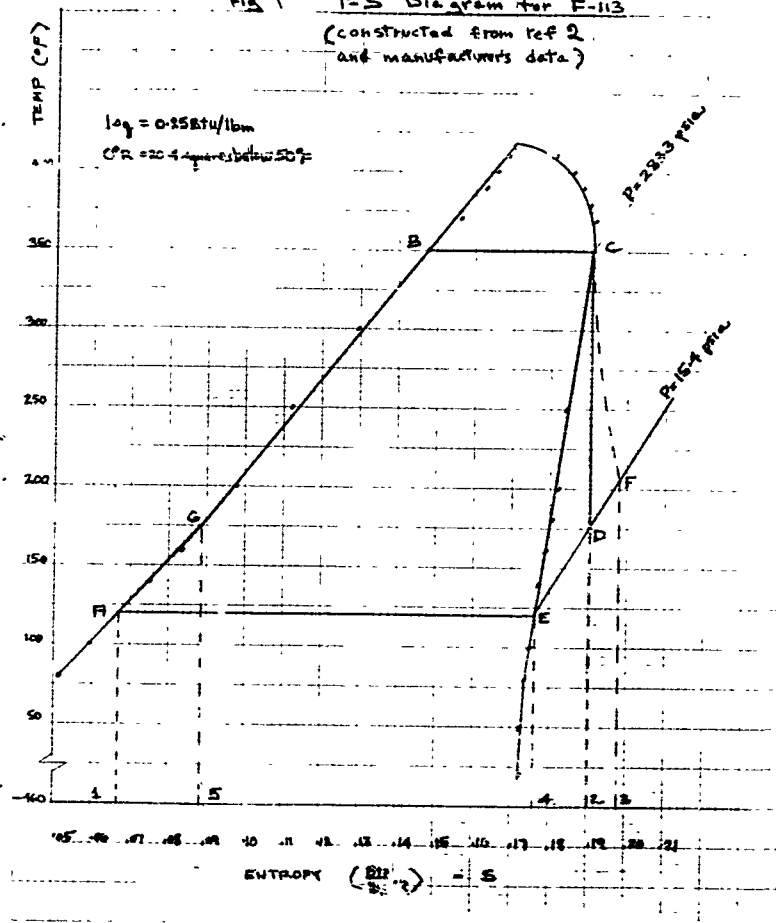
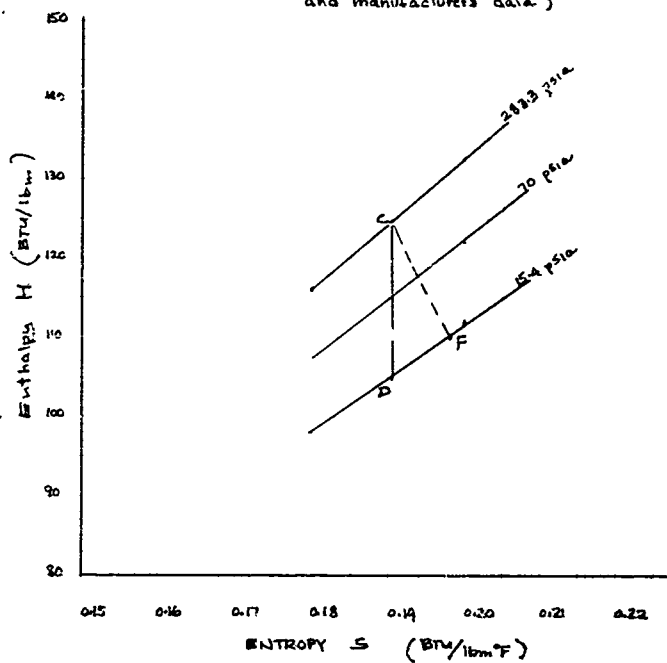
(constructed from ref 2  
and manufacturer's data)

Fig. 2. H-S Diagram for F-113(constructed from ref 2  
and manufacturer's data)

Nozzle Exit and Blade Dimension CalculationNozzle Exit

Steam flow = 0.834 lb.<sub>m</sub>/sec.

(If the nozzle exit pressure is less than the critical pressure, supersonic flow exists and converging-diverging nozzles are required).

Considering conditions at the nozzle exits.

$$W = \rho_1 V_1 A_1$$

where  $A_1$  = total of nozzle exit areas.

$\rho_1$  -- exit density determined by exit pressure and enthalpy ( $h_{\text{exit}}$ )

Taking reheat into account, with nozzle efficiency 0.9

$$h_{\text{exit}} = 105 + 19.8 (1 - 0.9) = 106.92 \text{ BTU/lb.}_m$$

From ref. (2) chart, estimate  $\rho_1 = 0.415 \text{ lb.}_m/\text{ft.}^3$

$$\text{Then } A_1 = \frac{0.834 \times 144}{0.415 \times 947} = 0.306 \text{ sq. ins.}$$

Assume only one nozzle is to be used

Then  $A_1$  per nozzle = 0.306 sq. ins.

$$\text{and } D_1 = \sqrt{\frac{0.306}{\pi}} \times 4 = .62" \text{ (Round nozzle)}$$

Blade height at entrance

The minimum recommended height is 3/8" or 2% of diameter. The blade height is also usually slightly larger than the nozzle height. Therefore take blade height 0.68 which is an increase of 10%

Blade Height at Exit. ( $l_2$ )

By the continuity equation,

If reheat is neglected, the following relation applies (ref. 4)

$$l_{\text{exit}} (\text{nozzle}) V_1 \sin \alpha_1 = l_2 u_2 \sin \beta_2$$

where  $l$  is the height

$$\text{Then } l_2 = \frac{0.62 \times 947 \times 0.342}{467 \times 0.4226} = 1.015''$$

Note how  $l_2$  may be reduced by increasing  $\beta_2$

The effect of the reduction in density  $\rho_1$  due to reheat may be taken into account as in the nozzle calculation

Blade Pitch

$$\text{Pitch} = \frac{\text{nozzle diameter}}{\sin \alpha_1 \times m}$$

Where  $m$  = (pitch - edge thickness) / pitch

An initial estimate of  $m$  may be taken as 0.94

Then

$$\text{pitch} = \frac{0.62}{0.342 \times .94} = 1.93''$$

This should be checked against the previous expression for best pitch.

Number of blades on 1 ft. disc

$$= \frac{\pi \times 12}{1.93} = 19.6$$

Then use 20 blades.

Note that if only one nozzle is used, there is partial admission and blade windage losses which must be included in the determination of turbine efficiency

## SECTION II Reaction Turbine

Introduction

The feature of a reaction turbine is that the working vapour undergoes expansion in the moving blades as well as in fixed nozzle-blades

An additional characteristic of reaction turbines is that full admission is a necessity in order to avoid intolerable leakages

Performance curves for this turbine are shown in ref. (3). They indicate that  $\lambda$  can be varied to a greater extent than in impulse turbines without adverse effects on efficiency. On the other hand they also show that  $\eta_e$  is very sensitive to changes in enthalpy drop per stage at any given blade speed, and that  $\eta_e$  for the reaction turbine can be higher than that for the impulse wheel over only a very small enthalpy range. Design of a reaction turbine must also take into account the axial thrust that exists across the moving disc due to pressure difference across the blades.

These turbines are usually classified by the proportion of enthalpy drop occurring in the moving blades,

$$\text{Degree of reaction} = \frac{\Delta h_b}{\Delta h_n + \Delta h_b}$$

In a single stage reaction turbine,

$$h_n = \frac{v_1^2}{g_c J \eta_{nr1}}$$

where the velocity of the vapour entering the first fixed blades has been neglected. The second part of the enthalpy drop is

$$\Delta h_b = \frac{u_2^2 - \phi u_1^2}{g_c J n}$$

The coefficient  $\phi$  is the carry-over coefficient and takes into account the losses between the exit of the fixed blades and entry to the moving blades. Data on  $\phi$  are scarce, but some guides are given in refs. 1 and 3.



The most widely used type of turbine has 50% reaction (Parsons turbine). In this type the enthalph drop in the fixed and moving blades is the same with the result that both sets of blades are identical and manufacturing expenses are reduced. For the 50% reaction turbine it can be shown that

$$\eta_B = \eta_n \frac{(2 \lambda \cos \alpha_1 - \phi^2)}{1 - \phi(1 + \lambda^2 - 2 \lambda \cos \alpha_1)}$$

and this time  $\eta_B$  becomes a maximum when  $\lambda = \cos \alpha_1$ . Actual stage efficiency  $\eta_e$  is further reduced because of disc friction and leakage losses past and tips of blades. This leakage is a function of the blade dimensions and radial clearance. It may be estimated by (1),

$$\text{leakage} = 3 \left( \frac{c}{\lambda} \right) \times \text{full flow}$$

where  $c$  = tip clearance

$\lambda$  = height of blade.

Percentage leakage losses are also plotted in ref. (4).

#### SAMPLE CALCULATIONS

Letting  $\alpha_1 = 20^\circ$

Percent reaction = 50%

and  $\Delta h_{1\text{sent.}} = 19.8 \text{ BTU/lb.}_m$  - for one complete stage.

Then  $h_n = 19.8/2 = 9.9 \text{ BTU/lb.}_m$

$$\text{and } V_1 = 223.8 \sqrt{0.9 \times 9.9} = 668 \text{ fps}$$

Where  $\eta_m$  is assumed = 0.9

Letting  $\cos \alpha_1 = 0.94$

Velocity diagram

Scale 1" = 200 fps

For 50% reaction,

Now

$$\Delta h_b = \frac{U_2^2 - \phi U_2^1}{2g_c J \eta_n}$$

Assume  $\phi = 0.75$  -- see ref. (3)Assume  $\eta_n = 0.9$ 

Then

$$9.9 = \frac{u_2^2 - 0.75 \times 226^2}{2 \times 770 \times 32.2 \times 0.9}$$

and  $u_2 = 690$  fps

Then blading efficiency

$$\eta_B = \frac{\text{Work out}}{\text{Energy supplied}} = \frac{W}{E}$$

For 0.834 lb./sec. flow (as previously)

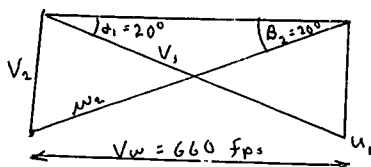
$$W = 0.834 \times 660 \times 627/32.2 \quad E = 19.8 \times 778 \times 0.834$$

Assume 5% leakage loss (see ref. 4)

Then

$$\eta_B = \frac{660 \times 627}{32.2 \times 19.8 \times 778} \times 0.95 = 0.79$$

In addition, the loss due to disc friction exists. To obtain an engine efficiency  $\eta_b$  losses (b) must also be added in.



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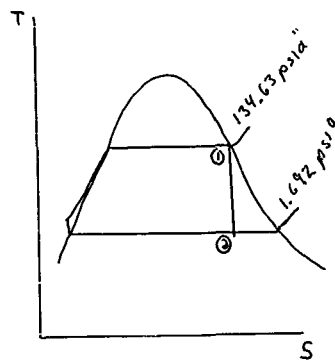
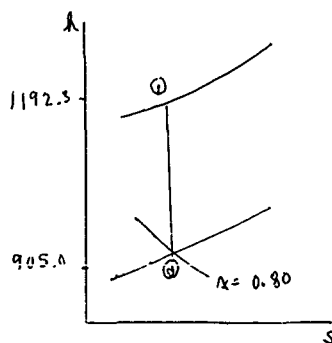
## NOMENCLATURE

F	Force on blade	$\sum \frac{m}{g_c} (V_{1x} \rightarrow V_{2x}) = \frac{m}{g_c} \sum V_w$
$g_c$		$32.2 \frac{\text{lb. mft.}}{\text{wt. sec}^2}$
U	blade speed (mean)	
$\lambda$		$u/V_1$
$V_1$	absolute velocity of vapour striking blade at inlet	
C		$\cos \beta_2 / \cos \beta_1$
$\beta_1$	Blade inlet angle	
$\beta_2$	Blade exit angle	
$\alpha_1$	Vapour inlet angle (nozzle angle)	
$\alpha_2$	Vapour exit angle	
$u_1$	Vapour velocity relative to blade at inlet	
$u_2$	Vapour velocity relative to blade at outlet	
R	Disc radius	
$\omega$	Angular velocity of disc	
J		$778 \text{ ft. -lb. / BTU}$
m	mass flow	$\text{lb.}_m / \text{sec}$
$\Delta h_b$	Enthalpy drop across moving blades in a Reaction Turbine	
$\Delta h_n$	Enthalpy drop across fixed blades in a Reaction Turbine	
$\mu$	Viscosity	
$k_b$	Blade coefficient	
$k_n$	Nozzle coefficient	

## APPENDIX

Abridged Calculation for Steam

$$\begin{array}{lll}
 T_1 = 350\text{F} & P = 134.63 \text{ psia} & h_g = 1192.3 \\
 T_2 = 120\text{F} & P_2 = 1.692 \text{ psia} & h = 905.0 \\
 x = 0.8
 \end{array}$$



$$\Delta H = 1192.3 - 905 = 287 \text{ B/lb}_m$$

$$\text{Assume nozzle eff.} = 0.92$$

$$V_o = 223.8 \sqrt{0.92 \times 287.3} = 3,640 \text{ fps.}$$

$$\text{But maximum common blade speed} = 750 \text{ fps} = u$$

$$\cos \alpha_1 = \frac{u}{V_o} = \frac{750}{3,640} = 0.206 = \frac{\cos \alpha_1}{2}$$

$$\alpha_1 = 66^\circ$$

# Velocity Diagram

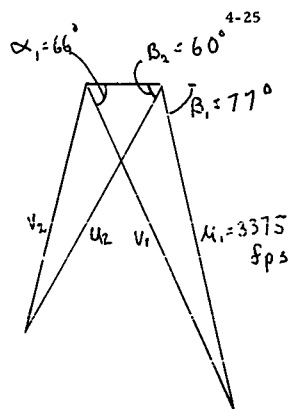
Let 1" = 1,000 fps.

take  $k_p = 0.86$

$$B_2 = 60^\circ$$

$$u_2 = 0.86 \times 3375$$

$$= 2900$$



$$\begin{aligned} \text{Then } \eta_B &= 2 \times 0.206 (0.206 - 0.206) \left( 1 + 0.86 \times \frac{0.5}{0.225} \right) \\ &= 0.234 \end{aligned}$$

Then useful work out - even if all other losses are ignored

$$= 287.3 \times 0.92 \times 0.234 = 62 \text{ B/lb.m}$$

$$\text{and overall eff} = \frac{62}{1104} \times 100 = \underline{5.5\%}$$

## APPENDIX 5 POSSIBLE MODIFICATIONS TO ENGINE GENERATION SETS

### Introduction and Summary

Engine generator sets are in general satisfactory for the shelter application. However, there are certain modifications to the set itself, and auxiliary components that would improve the utilization of engine generator sets for the shelter application. These are:

1. A unit for cleaning the engine block water so that potable hot water could be obtained directly from the engine cooling system without the utilization of heat exchangers.
2. A unit for cleaning of air that passes over the set so that the air warmed by radiation and low temperature convection would be sufficiently clean for shelter heating applications such as chill removal and clothes drying.
3. The moisture in the exhaust gases could be condensed and purified.

### Technical Discussion

#### Water Cleaning Unit

Figure I shows a schematic diagram of the way a water treatment cartridge would be used to clean up water from an engine cooling system. Normally, water flows from the engine block, through the pump, through open valve 3, to the external radiator and back to the engine block. When it is desired to clean up the water for a potable hot water supply, valve 3 is closed and valves 1 and 2 are opened. This bypasses the engine cooling water through the water treatment cartridge, where sediment and dissolved impurities are removed.

Figure II shows a schematic layout of how the water treatment cartridge might be made up. Water flowing through valve 1 goes to chamber A, where the entrained solids are removed with diatomaceous earth filter. Passing to chamber B, an ion exchange resin bed removes dissolved inorganic matter, and the water flows out (through passage F) to the external radiator. This portion of the arrangement allows for sufficient flow rate to keep the engine cooled at all times.

An opening from chamber B into chamber E (containing activated carbon), and a connection from chamber E back to the suction side of the pump through valve 4 permits a bypassing of a part of the water through the activated carbon bed, where organic materials are absorbed from the water.

When the clean-up process has been carried on long enough to provide a potable water (the clean-up operation is an exponential function and provides a relatively fast cleaning operation) hot water can be drawn off through the activated carbon bed E and through valve 7, or the water can be passed through a disinfecting chamber, and potable drinking water removed at valve 6.

As a potential multiple use of the water treatment cartridge, it is possible to connect the cartridge to an impure water source by valve 8 (with valves 1 and 2 closed and valve 3 open) and to remove potable water at valves 6 or 7.

Since it is necessary to supply water to the cooling system any time hot water is drawn from it, a line from a potable water supply can be connected through valve 9 to the cooling water system.

#### The Engine as an Air Heater

The radiant heat loss and the convection heat loss from a liquid cooled engine (exclusive of the cooling water heat removal) is waste heat that must be either utilized or rejected in the shelter. The salvaging of this heat by heat exchangers would be costly due to the relatively low temperature differentials combined with the low gas to gas over-all heat exchange coefficients. The direct utilization of the air that pass over the engine generator set and radiation receiving surfaces would eliminate the need for the heat exchanger but would require that provisions be taken to prevent contamination of the shelter air. There are several aspects to this decontamination problem that require evaluation.

- a. Utilization of porous membranes and filters
- b. Utilization of electrostatically charged membranes
- c. Utilization of activated charcoal.

Therefore, it is suggested that these phenomena be evaluated from the standpoints of pressure drop, reliability, unit size and cost for the shelter application.

The air temperature of the processed air would be in an ideal range for space heating (removal of chill) and cloth (clothes, etc.) drying for the temperature range of this air is such that high temperature and limiting controls would be unnecessary.



#### Water From Exhaust Gas

Since the possibility of salvaging water from the combustion in a hydrogen oxygen fuel cell is mentioned, the possibility of obtaining water from the the exhaust gases of an engine generator set is also mentioned.

Both of these sources of water are contaminated. The fuel cell rejected water contains electrolyte and the engine rejected water contains dissolved flue gases. Both of these waters can be purified. The main difference between these waters is that due to the comparative efficiency and fuel cost, more and cheaper water would be available from the engine generator set. However, the water from the engine would be in the gaseous state and require condensing. This would be favorable or unfavorable depending upon the ability of the particular shelter to use and/or reject this heat of condensation.

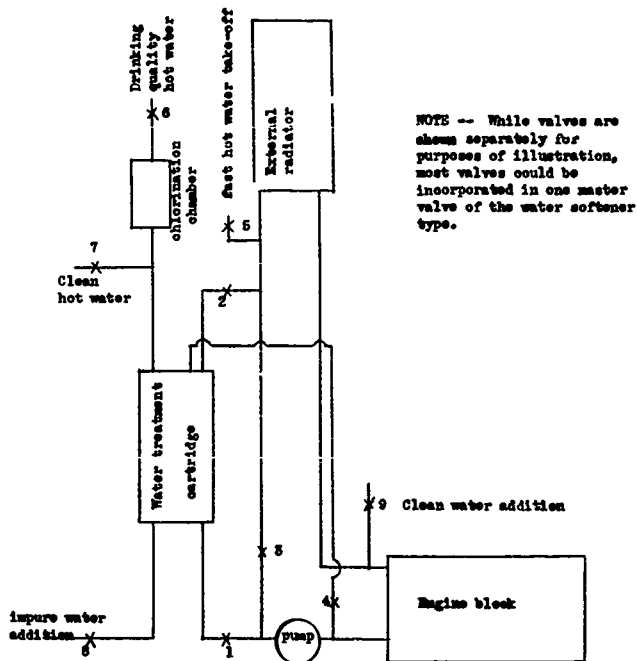


FIG. 1 SCHEMATIC DIAGRAM OF WATER CLEANING SYSTEM

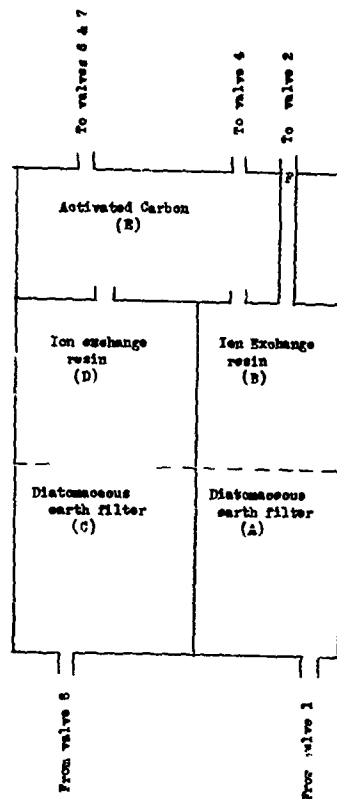


FIG. II Schematic construction of water treatment cartridge

## APPENDIX 6 BOILING AND CONDENSING-VAPOR HEAT TRANSFER

### Introduction

A device known as a "heat tube" definitely has a potential application in fallout shelters. Therefore this section is devoted to means for assigning numerical values to the thermodynamic characteristics of mass transfer and heat transfer in a heat tube.

### Description of a Heat Tube

A typical heat tube (sometimes known as a "thermal diode") is shown in Fig. 1. The device consists of a thin-wall tube filled with a refrigerant having a vapor pressure of a few atmospheres in the expected range of operation. If the heat transfer to the tube is from or to a gas, extended surfaces (fins) would probably be used to increase the capacity of the heat tube.

In operation, heat is transferred through the wall at the bottom of the tube. Boiling heat transfer coefficient between the wall and refrigerant result in a very low resistance to heat transfer. Hence, the heat transfer resistance for heat exchange between shelter air and the heat tube is essentially due to the low heat transfer coefficients of air flowing over the tube. The resulting vapor will flow upward if the top surface of the tube is at a lower temperature due to the fact that the vapor pressure of the refrigerant decreases with temperature. Condensation (with relatively large heat transfer coefficients) occurs on the inside surface at the top of the tube, the condensate returns to the bottom under the influence of gravity. If heat is being rejected to the outside air, the heat transfer resistance at the top of the tube is essentially due to the heat transfer coefficient for air flowing over the tube.

The true value of the heat tube (and reason for the name "thermal diode") is due to the essentially one-way heat transfer in the device. If the top of the tube should become hotter than the bottom (as in the case of a fire storm or other nearby heat source), the heat would be transferred into the shelter by conduction in the metal tube wall and stagnant refrigerant vapor. Both of these processes result in very low heat transfer rates. Thus the heat tube is a reliable device (without moving parts) which cools the shelter air when conditions are favorable and allows very little heating of shelter air when conditions are unfavorable.

### Analysis of the Heat Tube

#### A. Single, Bare Tube

The notation in Figure 1 is used in this section to obtain some idea of the performance of a single heat tube

It is assumed that an air velocity inside the shelter (due to possible use of fans) and a wind velocity outside the shelter will probably not exceed 10 miles per hour. Thus a tube with a diameter of approximately 0.1 ft. with air at atmospheric temperature and pressure flowing over it will have a Reynolds number of between zero and 10,000 (using the outside tube diameter and free-stream air velocity as the characteristic diameter and velocity respectively in the Reynolds number).

The results of many heat transfer experiments for air flowing over tubes are shown in Figure 10-7 of Reference 1. A reasonable approximation of the Nusselt number as a function of the Reynolds number over the range of interest is given by

$$Nu = 0.6 Re^{.5} \quad (1)$$

where the characteristic diameter in the Nusselt number is the outside diameter of the tube.

It will be assumed that the tube may be considered a conductor having infinite thermal conductivity for heat transfer rates expected to occur for typical temperature differences between the shelter and ambient air. This assumption will be verified later. Thus the temperature of the tube surface,  $t_b$ , is the same inside and outside the shelter (see Fig. 1). It is further assumed that no heat loss occurs from the section of the tube passing through the earth above the shelter

A heat balance on the heat tube thus yields

$$Q = h_i A_i (t_i - t_b) = h_o A_o (t_b - t_o) \quad (2)$$

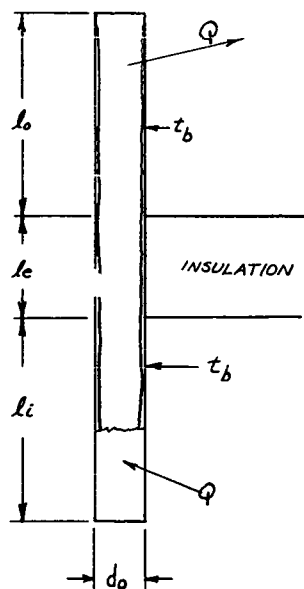
where the "i" and "o" subscripts refer to inside and outside heat transfer coefficients ( $h$ ), tube surface areas ( $A$ ), and air temperatures ( $t$ ) respectively. The units of  $Q$  are Btu/hr.

Since the heat transfer for a given tube is essentially dependent on air velocity ( $U$ ) and the temperature difference ( $\Delta t$ ) between the shelter and ambient air, Eqs. 1 and 2 may be solved simultaneously (along with an expression of tube lengths for surface areas) to yield

$$Q/\Delta t = 0.6 \pi U_1^{.5} k (d_o/\Delta)^{.5} / [1 + (1/10) (U_1/U_o)^{.5}] \quad (3)$$

where  $k$  and  $\Delta$  are the thermal conductivity and kinematic viscosity of the air respectively.

$t_o$  = OUTSIDE AIR TEMPERATURE



$t_i$  = INSIDE AIR TEMPERATURE

FIG. 1 HEAT TUBE

The thermal conductivity of air at atmospheric temperature and pressure is approximately 0.015 Btu/hr ft °F, while the kinematic viscosity is  $1.688 \times 10^{-4}$  ft<sup>2</sup>/sec. Thus for a tube with a one-inch outside diameter exchanging heat from shelter air to outside air at nearly atmospheric temperature and pressure, Eq. 3 becomes quite simply

$$Q/\Delta t \cdot l_1 = 0.626 U_1^{.5} / [1 + (l_1/l_o) (U_1/U_o)^{.5}] \quad (4)$$

Eq. 4 is plotted in Figs. 2, 3 and 4 for several ratios of inside-to-outside tube lengths and air velocities.

As an example, Fig. 3 shows that if the ratio of the length of tube inside the shelter to the length of tube outside the shelter is unity, the ratio of the inside to outside air velocity is unity, and the inside air velocity is 4 feet per second, then 0.625 Btu/hr. will be transferred per foot of tube per degree difference between the inside and outside air temperature. It must be remembered that Figs. 2, 3 and 4 were constructed for a 1 in. O.D. tube, similar figures could be constructed (using Eq. 3) for other tube diameters.

#### B Banks of Bare Tubes

Generally tubes such as the one shown in Fig. 1 would be used in banks rather than singly. The correlations between Nusselt number and Reynolds number become more complex as additional factors such as arrangement (in-line or staggered), spacing, and depth of the bank enter the correlation. Reference 1 contains much factual information on heat transfer to tube banks. In summary, however, it may be stated that for tube banks:

1. The first row of the bank yields heat transfer coefficients nearly identical to those of single, bare tubes.
2. The average heat transfer coefficient increases with the number of rows of tubes in the flow direction up to ten rows. Tube banks with ten or more rows may show average heat transfer coefficients 30 to 40 per cent greater than that of a single, bare tube.
3. The relationships given in the single, bare tube analysis would thus be conservative if used for analysis of tube banks.

#### C Banks of Finned Tubes

Although finned tubes are used extensively in refrigeration and air conditioning, the available data are largely empirical. Reference 2 presents much of the more reliable data in fundamental form. In general the finned-tube exchangers are used in banks, and the heat transfer may be increased over banks of bare tubes. A comparison

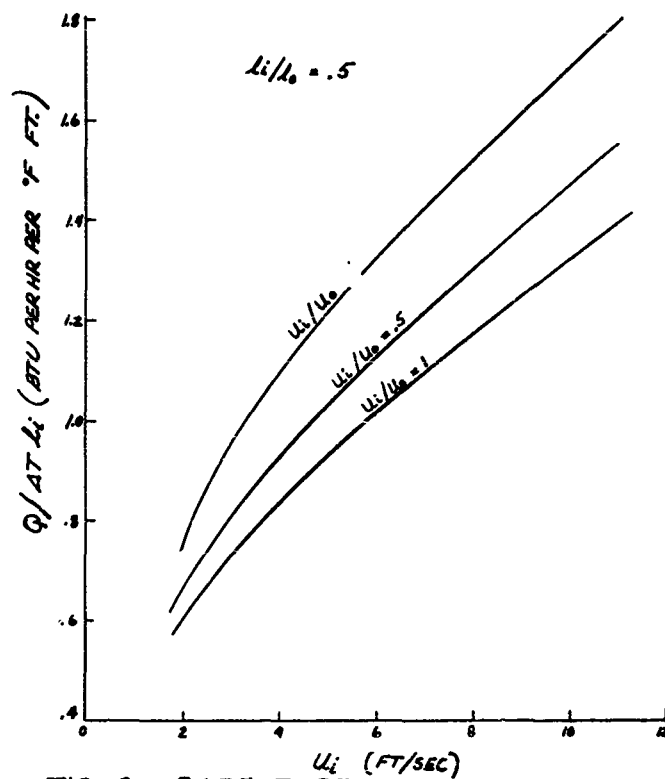


FIG. 2 BARE TUBE HEAT TRANSFER



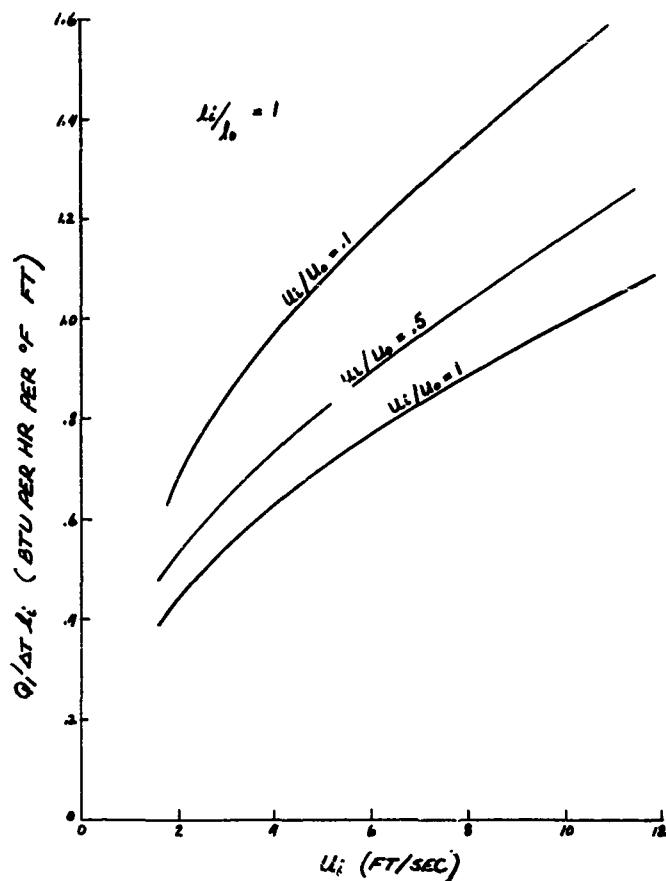


FIG. 3 BARE TUBE HEAT TRANSFER

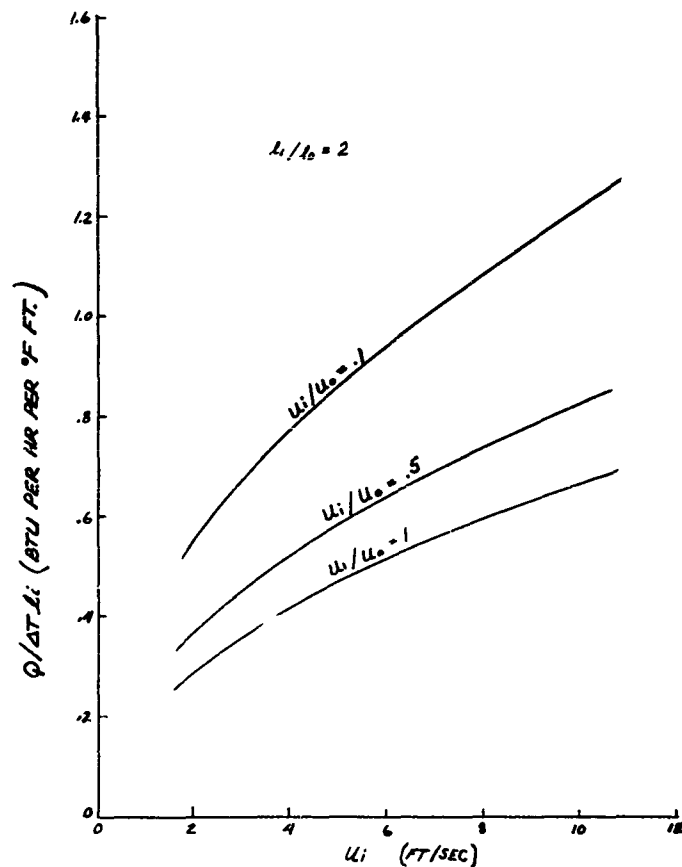


FIG. 4 BARE TUBE HEAT TRANSFER

of Fig. 99 and Fig. 56 of Ref. 2 (even though the figures are not entirely comparable) indicates an increase of the ordinate by a factor of nearly 3 for the finned-tube bank over the bare-tube bank. However, the friction loss through a finned-tube bank must be higher for the same flow rate; thus more power is required for air circulation.

#### D. Analysis of Refrigerant Flow

From section A it was seen that a heat transfer rate of 0.625 Btu/hr per foot of inside tube per degree temperature difference between the shelter and ambient air could be expected. Thus a 4 foot tube length in the shelter and a temperature difference of 20°F would result in a heat transfer rate of 50 Btu/hr. It was shown in section C that a finned tube could increase this to approximately 150 Btu/hr.

Assuming that the refrigerant in the tube is methyl chloride with a latent heat of vaporization of approximately 160 Btu/lb., the flow rate in the tube would be approximately one pound per hour or  $2.78 \times 10^{-4}$  lb./sec.

A well-known relationship between pressure drop in a tube and fluid flow rate for developed flow is given in Ref. 3 as

$$\Delta P = 2\rho V^2 L f / g_c D \quad (\text{lb}_f/\text{ft}^2) \quad (5)$$

where

- $\rho$  is the fluid density (lb/ft<sup>3</sup>)
- $V$  is the fluid velocity (ft/sec)
- $L$  is the tube length (ft)
- $D$  is the tube diameter (ft)
- $f$  is the friction factor
- $g_c$  is a conversion factor (32.2 lb ft/lb<sub>f</sub>sec<sup>2</sup>)

Assuming that the flow is laminar, the friction factor is given simply as

$$f = 16/\text{Re} \quad (6)$$

where Re is the Reynolds number using the inside diameter of the tube as the characteristic length and the flow velocity as the characteristic velocity.

The continuity equation requires that

$$W = \rho AV \quad (7)$$

where W is the mass flow rate (lb./sec) and A is the inside cross sectional area of the tube (ft<sup>2</sup>). Combining Eqs. 5, 6 and 7, the relationship between pressure drop and mass flow rate becomes

$$\Delta P = 128 WL / (\pi D^4 g_c) \quad (8)$$

where  $\nu$  is the kinematic viscosity ( $\text{ft}^2/\text{sec}$ ).

The kinematic viscosity of saturated methyl chloride vapor at room temperature is  $7.78 \times 10^{-6} \text{ ft}^2/\text{sec}$ . Hence, the pressure drop for a tube 10 ft long with a 0.9 in. inside diameter and a mass flow rate of 1 lb of methyl chloride per hour is  $6.01 \times 10^{-6} \text{ lb}_f/\text{in.}^2$ . A table of vapor pressure vs. temperature for saturated methyl chloride near room temperature indicates a pressure change of 1.4 psi/°F. Hence, the assumption in part A that the tube is a perfect conductor is verified.

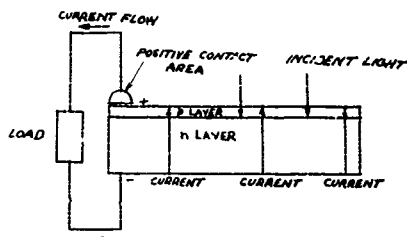
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### Principle of Generation of Electricity

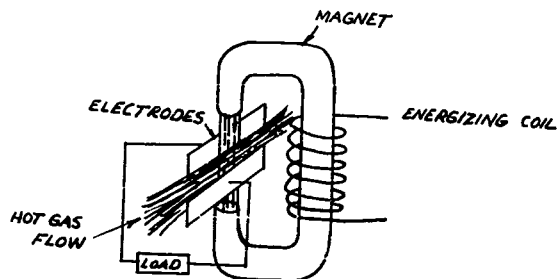
Electrons, like gases, tend to distribute themselves uniformly in a closed system. If energy is properly applied to a section of the system, this uniformity can be disturbed. When the system attempts to restore its uniformity, electrons flow and the result is an electric current.

The newer energy conversion devices can be described in these terms and the following is a "standardized" description for comparison of modes of operation



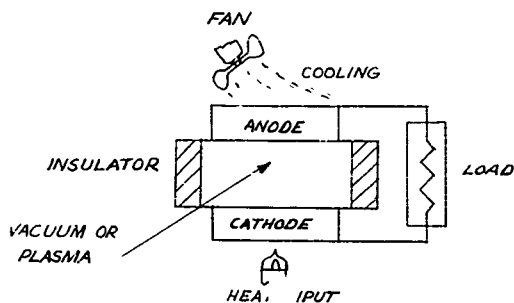
PHOTOVOLTAIC CELL

Light rays resonating near the interface of a "p" and "n" materials junction cause the electrons to flow from the "p" material to the "n" material. These electrons return via an external electrical circuit to the "p" material; hence, electricity flows.



MHD GENERATOR

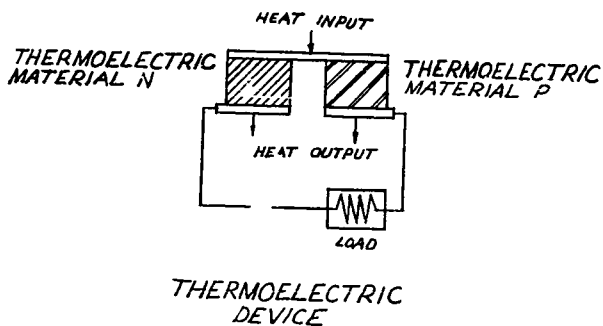
The magneto hydro-dynamic generator uses a powerful magnet to cause electrons to concentrate on one side of a moving hot gas stream. This produces an electron concentration gradient (commonly called voltage) that causes the flow of electricity through an external electrical circuit connected to electrodes on opposite sides of the hot gas stream. Hot gases contain free electrons for this electron flow process because of thermal ionization or ionization due to a seeding process (addition of easily ionized materials).



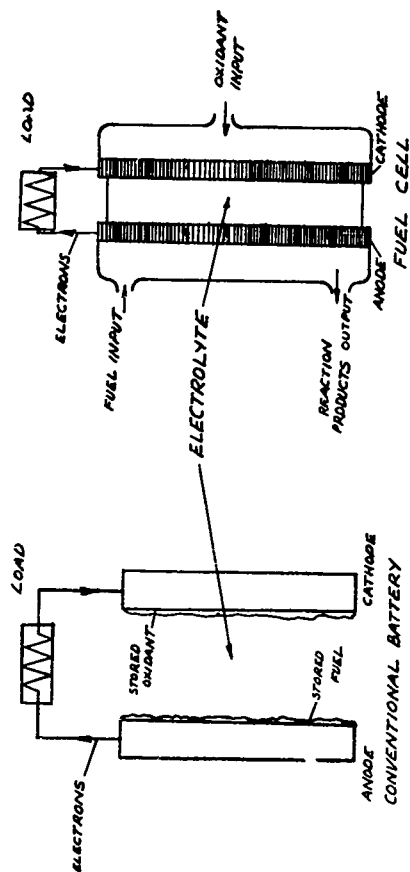
### THERMIONIC DIODE

In a thermionic device, heating a material (the cathode) to sufficiently high temperatures cause electrons to "boil" out of the metal. These electrons "condense" on the anode and consequently tend to concentrate there. This "concentration" results in a voltage between the anode and cathode and a subsequent electron flow in an external circuit.





The thermoelectric device operates as a powerful thermocouple. A temperature differential causes electrons to flow in each leg of the couple. This creates an electron concentration gradient (commonly called voltage) that causes electricity to flow in an external circuit. Some materials cause electrons to concentrate at the hot junction and others at the cold junction. Proper selection of materials optimizes the over-all resultant voltage.



The conventional battery stores chemical energy that is converted to electrical energy when the electric circuit is closed. The reaction products remain in the cell.

The fuel cell has an external source of chemical energy and the reaction products are removed from the cell. The general principle of operation is similar to that of the storage battery. However, the electricity-producing reaction is complicated by the need for the mass flow of reactants and products into and out of the cell.

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